CHEMICAL ENGINEERING 8 ROTATING EQUIPMENT • OVERPRESSURE PROTECTION VOL. 125 NO. 3 MARCH 2018

CHEMICAL ENGINEERING

March 2018

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Overpressure Protection

Solar Chemistry

Air Filtration

Facts at Your Fingertips: Combustion

New PPE Regulations

Focus on Control Hardware

Isopropanol Production

Designing Smarter Rotating Machines

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Cover design: Rob Hudgins

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Editor's Page

A plug for 'big science'

One of the first experiments I ever conducted in my basement chemistry lab was to split water into hydrogen and oxygen, using the transformer from my train set as the power supply and platinum ribbon strips as electrodes. Although most *CE* readers have at least seen this demonstrated in their elementary school days, for me, the excitement was not the mini "explosion" that occurs when you light the H_2 with a match, or the just-extinguished match bursting into flame in the O_2, but the observation that the volume ratio of H_2 to O_2 was two. Perhaps this elegant demonstration of water's composition was a spark that led me to go into science in the first place.

At that period in my life, I was also glued to the black-and-white television screen watching the Apollo space missions. So enthralled was I with these endeavors, that I had pictures of the moon launches and landings on my bedroom wall. Last month, some of this child-like enthusiasm returned, for two reasons. First, the February 6 launch of the Falcon Heavy in itself was awe inspiring, but when the two rocket boosters returned to earth and landed almost simultaneously in an upright position, I was astonished at that engineering achievement. It reminded me of science-fiction movies from the 1950s.

Secondly, working on this month's Newsfront on solar chemistry (pp. 12–16) reminded me of the thrill of watching bubbles of H_2 and O_2 form on the electrodes of my basement electrolyzer. Yes, this process is so simple, that even a child can do it — but as a child, I was ignorant about the engineering and economic factors that are necessary to make this process feasible on a large scale.

Nevertheless, these two events — the Falcon Heavy Test Flight and writing about the "big science" projects related to solar chemistry that are going on at government research institutes, universities and industry — bring home important observations I made.

To do some really exciting science requires three things: a vision, educated people and money. In the space race of the 1960s, everything was paid for by the governments involved (ultimately, the tax payers), whereas much of the Falcon Heavy launch was a private venture of a man with a vision — Elon Musk, the CEO of SpaceX and Tesla. In both cases, thousands of talented scientists and engineers were employed.

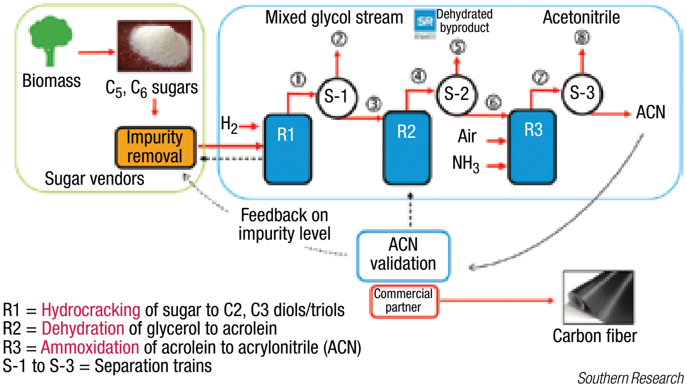
With regards to the big-science projects mentioned in this month's Newsfront article, the same three requirements seem to be present: countries (and industrial partners) with the vision to plan for the future; funding necessary to carry out the research and development that is needed; and thousands of talented scientists, materials chemists and engineers, who are being employed in some very exciting projects. Imagine the enthusiasm that is inspiring the next generation of engineers when their school trips take them to Sandia National Laboratories in Albuquerque, or the German Aerospace Center in Cologne to see water being split at temperatures up to 1,400°C using just concentrated sunlight and some minerals (a gross oversimplification).

So, I applaud those governments (and in some cases, at least individual states and cities) that continue to fund industry-academic "big science" projects for conducting basic research that eventually will lead to commercial applications — in this case, producing fuels and chemicals without coal, petroleum or gas. Judging from the progress being made in solar chemistry, Musk's vision of sending human colonies to Mars may be an option, but not a necessity. ■

Gerald Ondrey, Senior Editor

Catalytic conversion of sugars to acrylonitrile

Acrylonitrile (ACN) — a precursor in nearly all carbon fibers — is typically produced from propylene and ammonia, but a new method uses biomass-derived second-generation sugars. The process was developed by Southern Research (Durham, N.C.; www.southernresearch.org) and seeks to provide a more sustainable drop-in source of ACN. In this three-step process (diagram), aqueous lignocellulosic sugars are converted to multifunctional alcohols, which undergo dehydration to acrolein before a final ammoxidation step to yield ACN. This continuous fixed-bed process has a small footprint that would fit well into chemical-processing sites while utilizing a versatile feedstock, says Bill Grieco, vice president of energy and environmental activities at Southern Research. "We see high selectivity and high conversion in this process without the downstream separations that biological processes typically have to deal with," he explains. Each reaction step uses a heterogeneous catalyst; the first two steps involve newly developed catalysts, and the third step uses an established catalyst that has been adapted to accommodate this particular process.



Southern Research

The team has evaluated the process using a wide range of sugar feedstocks. "Basically, it doesn't matter what blend of sugars we use. There is no change in catalyst configuration. Very minor changes in reaction conditions can yield the same product slate," explains Amit Goyal, project manager. Typically, says Goyal, the catalysts used for these types of sugar conversions are very unstable, especially in aqueous conditions, but the catalyst system developed by Southern Research boasts longterm stability over a wide range of operating conditions. Another benefit is the ability of the system to handle feedstock impurities. "We have tested several organic and inorganic impurities at different levels to make sure the catalyst stability is not compromised, while still meeting product specifications," says Goyal.

The team has demonstrated continuous production of a few grams of ACN per hour, and a pilot plant, slated for completion in October 2018, will expand production to the kilogram scale. The produced ACN is validated by Cytec, a Solvay group company (Greenville, S.C.; www.cytec.com).

A more direct chemical route to ketones

Using a simple, ligand-free palladium catalyst system, researchers at McGill University (Montreal, Que., Canada; www.mcgill.ca) have demonstrated that metal carbonylation — a core chemical reaction for many industrial products — can be used to synthesize ketones directly from hydrocarbons. The most common method for synthesizing ketones is the Friedel-Crafts reaction, which requires several energy-intensive preliminary steps to build up the required reactive acylating agents. The key to McGill's new route is the formation of a highly potent electrophile species from carbon monoxide itself, which can promote the synthesis of ketone compounds from commonly available hydrocarbons, such as benzene. Although ketone synthesis via carbonylation has been previously demonstrated, these less-direct methods required stoichiometric amounts of synthetic building blocks and created more chemical waste, explains Bruce Arndtsen, McGill chemistry professor. This reaction is run at relatively mild conditions — pressures of 4 atm and temperatures around 100–130°C. Since metal-catalyzed carbonylation is already a well-established core chemical platform, this process should be well suited for scaleup, mentions Arndtsen. The team has used a homogenous catalyst for their work thus far, but the simplicity of the system (no catalyst ligands are required) may make the process amenable to heterogeneous catalysis as well, he points out. Investigating potential heterogeneous catalyst systems will be a next step of the research, and will be important in scaling up the technology, since it would lend itself to catalyst recovery and lower overall costs.

Edited by:
Gerald Ondrey

GLYCOLIC ACID

Researchers from the group of professor Miho Yamauchi at the International Institute for Carbon-Neutral Energy Research (I2CNER) of Kyushu University (Fukuoka City, Ito Campus, i2cner.kyushu-u.ac.jp) have fabricated a liquid flow-type electrolyzer that can continuously produce an alcohol from a carboxylic acid using a polymer electrolyte. Dubbed PEAEC (polymer electrolyte alcohol electrosynthesis cell), the system has been shown to produce glycolic acid from oxalic acid using a porous TiO_2 (anatase) catalyst.

The catalyst is directly grown on a Ti mesh (TiO_2/Ti-M) or Ti felt (TiO_2/Ti-F), which is used as the cathode. The anode — IrO_2 supported on a gas-diffusion carbon electrode (IrO_2/C) — is separated from the cathode by a Nafion 117 membrane. With this assembly, a maximum energy conversion efficiency of 49.6% was observed, and a 99.8% continuous conversion of oxalic acid was achieved at room temperature.

Because glycolic acid is a stable compound with high energy density, it is a promising candidate for use in energy storage and transport. This electrochemical system offers a possible way to store excess wind or solar electricity.

HAFNIUM OXIDES

Australian Strategic Minerals Ltd., a wholly owned subsidiary of Alkane Resources Ltd. (Perth, Western Ausralia; www.alkane.com.au), has developed high-purity (99.8%) hafnium dioxide (HfO_2) products and 99.9% $(Hf+Zr)O_2$. Hafnium dioxide is a precursor for metallic hafnium used in superalloys

(Continues on p. 6)

and other aerospace alloys.

The products were obtained by a proprietary process at the demonstration pilot plant at the Australian Nuclear Science and Technology Organization (ANSTO; Sydney; www.ansto.gov.au). Process development, including improved metal recovery, water recycling and value engineering, are continuing on the plant at ANSTO and through a front-end engineering and design.

The mineral containing hafnium and zirconium, eudialyte, originates from the company's Dubbo Zirconia Project, a large in-ground resource of zirconium, hafnium, niobium, tantalum and yttrium, located 25 km south of the city of Dubbo, about 400 km from Sydney, in Central West New South Wales.

The process flowsheet (see online at www.chemengonline.com) for the Dubbo Project consists of a sulfuric acid leach followed by solvent extraction separation, chemical recovery and refining to produce zirconium, hafnium, niobium and rare earth elements.

The Dubbo Project represents a unique source of hafnium that is independent of all traditional markets, including China. According to Alkane, the Dubbo Project is the most advanced poly-metallic project of its kind outside China. It has a potential mine life of more than 70 years. Start-up volumes of production at Australian Strategic Minerals' processing plant will be about 25 ton/yr of Hf metal (30 ton/yr of HfO_2). Full plant capacity is estimated at 200 ton/yr.

NEW FCC CATALYST

Last month, BASF SE (Ludwigshafen, Germany; www.basf.com) commercially launched Boroflex, the latest evolution of its residuum (resid) oil fluid catalytic cracking (FCC) catalysts for the petroleum-refining sector. Boroflex is based on BASF's Boron-Based Technology (BBT), and is designed to optimize refiners' bottoms upgrading and distillate yields by providing maximum nickel contamination passivation.

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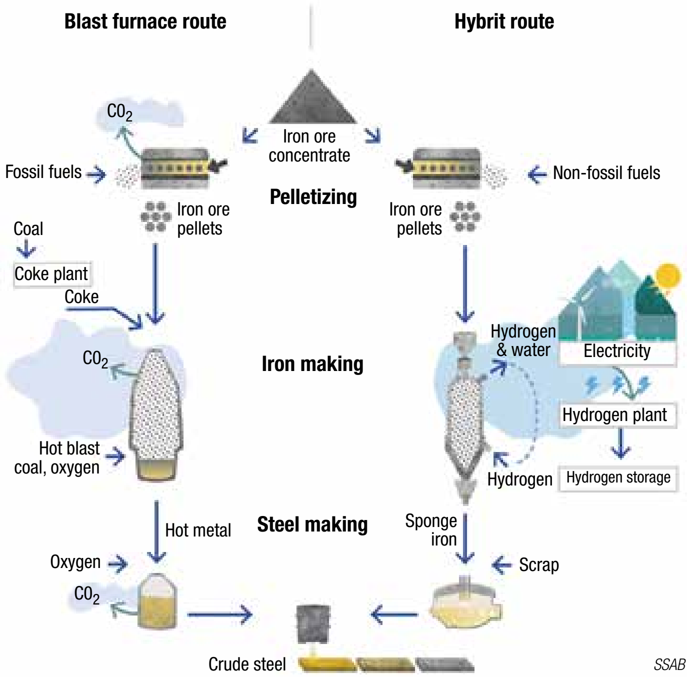
A push for 'green' steel



SSAB

Last month, the so-called Hybrit initiative (www.hybritdevelopment.com) was given the go-ahead to build a pilot plant for making fossil-free steel. The announcement follows a pre-feasibility study conducted by Swedish partners SSAB AB (Stockholm; www.ssab.com), LKAB (Luleå; www.lkab.com) and Vattenfall AB (Solna; www.vattenfall.com). The partners are looking to invest SEK20 million (about \$2.5 million) to plan and design the pilot plant in Northern Sweden. The Swedish Energy Agency will finance parts of the project, and the initiative — which could reduce Sweden's total CO_2 emissions by 10% (and those of Finland by 7%), is said to be crucial if the country is to meet its goals of the Paris Agreement.

Currently, coal and coke, which are shipped to Sweden from Australia and other places, are used to reduce iron ore into iron (diagram, left). The idea behind Hybrit is to use H_2 instead, which has been produced with electricity from fossil-free Swedish sources (diagram, right).

The pilot plant will be built in Luleå using iron ore deposits from Norrbotten, with construction starting as soon as this summer. The goal is to have a totally fossil-free process for steel production by 2035.

SSAB aims to cut its joint CO_2 emissions in Sweden by 25% by as early as 2025, through conversion of the blast furnace in Oxelösund, Sweden. Between 2030–2040, the aim is to also convert the blast furnaces in Luleå, Sweden and Raahe, Finland to eliminate most of the remaining CO_2 emissions and to attain the target of being fossil-free by 2045.

A bio-based caprolactam joint-development project is now underway

Last month, Genomatica (San Diego, Calif.; www.genomatica.com) and Aquafil (Trento, Italy; www.aquafil.com) announced a partnership to commercialize a Genomatica process for making caprolactam derived from renewable feedstocks, rather than from petroleum. The cyclic amide caprolactam is a key intermediate for the production of nylon.

The two partners are advancing Genomatica's Geno CPL process, with the goal of arriving at a fully commercial process for making high-quality, bio-based caprolactam with economics that are competitive with conventional caprolactam. Genomatica has not yet commented on commercialization timelines and specific cost targets.

An important element of the process is a high-yield microorganism being engineered by Genomatica for the fermentation step of the process, which will use sugars from a variety of sources as the feedstock.

Aquafil is a leading producer of nylon with expertise in converting caprolactam to the synthetic polymer nylon-6. The company is focused on developing more sustainable processes for making the material, which has widespread use in apparel, carpeting and other markets. In work that is complementary to its project with Genomatica, Aquafil is also working on a process known as the Econyl Regeneration System to produce nylon from regenerated waste.

Genomatica has previously developed processes for other bio-based chemicals, such as 1,4-butane diol (BDO) — for which it was the winner of the 2013 Kirkpatrick Chemical Engineering Achievement Award (*Chem. Eng.,* November 2013, pp. 15–19) — 1,3-butylene glycol (BG) and butadiene.

SOLAR H_2

Researchers at the University of Twente's (the Netherlands; www.utwente.nl) MESA+ Institute for Nanotechnology research institute have developed a system for making hydrogen from water and sunlight, without precious-metal catalysts. The device consists of photocathodes made of silicone microwires (less than 0.1-mm long), with tips coated with a Ni–Mo catalyst. Photons are collected between the microwires, and the photochemical conversion to H_2 takes place at the tips. This decoupling of the location of light absorption and reaction, combined with optimizing the density and length of the microwires, enabled the scientists to achieve a maximum conversion efficiency (light-to-H_2) of 10.8% — the highest reported for a Si-based device. The study is described in a recent issue of *Nature Energy* (See also "Solar Chemistry Heats Up," on pp. 12–16).

CO_2 HYDROGENATION

Researchers from Utrecht University (the Netherlands; www.uu.nl), in collaboration with BASF, Lehigh University and the synchrotron facilities at the Paul Scherrer Institute, have found a way to study in detail the conversion of CO_2 into methane, and to determine the perfect size for the catalytic silica-supported nickel nanoclusters. Described in a recent issue of *Nature Catalysis*, the researchers found that Ni particles exhibit optimal catalytic activity at a size of 2.5 nm. They also found that a specific architecture of these tiny nickel particles facilitates the activation of CO_2. This basic research is expected to further the understanding of CO_2 reduction, which is important for developing new catalysts for making renewable synthesis gas (syngas; H_2 + CO) and liquid fuels.

METALS FROM ASH

SUEZ S.A. (Paris, France; www.suez.com) plans to build the first plant to use the company's proprietary Valomet process to recover non-ferrous metals from bottom ash, the residue left behind in waste-to-energy plants. The new plant will be built in the port area of Ghent, Belgium, with €1-million funding support from the Flemish government.

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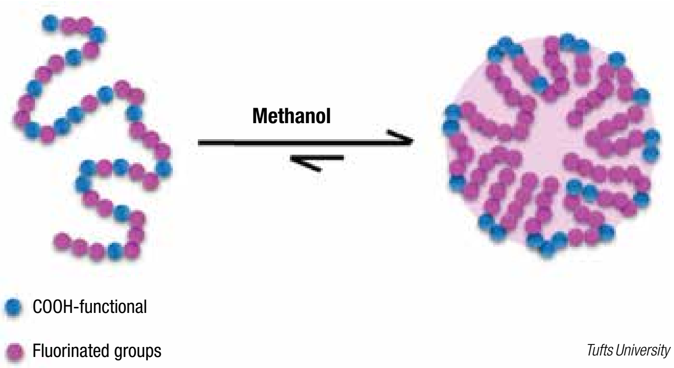
These highly selective membranes mimic biological ion channels



Tufts University

New membranes developed at Tufts University (Medford, Mass.; www.tufts.edu) can effectively separate similar chemicals based on not only size but on electrostatic charge. "Currently, there are no commercial membranes that are designed to separate organic molecules of similar size but different chemical structure," explains Ayse Asatekin, a chemical and biological engineering professor at Tufts. The membranes are created by coating a specialty polymer solution — a random copolymer of fluorinated methacrylate and methacrylic acid dissolved in methanol — onto a commercially available porous membrane. The polymer is synthesized in a single step via free-radical polymerization, which is an easily scalable process, explains Asatekin. She believes that this membrane-preparation process could be readily scaled up and adapted for commercial roll-to-roll manufacturing processes, enabling it to be installed into existing production sites with little modification.

What sets these membranes apart is the self-assembly of the polymer in solution to create micelles that form charged nanopores 1–3 nm in size (diagram). This enables a functionalized nanostructure that mimics biological pores, such as the ion channels that regulate the transport of chemicals in cell membranes. "Instead of using complex top-down methods to create these very small pores, we designed a polymer that will create them naturally due to its structure," says Asatekin. While other membranes have achieved similarly sized functionalized nanopores, the membrane preparation methods were more complex and the resulting membranes suffered from low porosity, making them more challenging to scale up, she adds. Due to the highly functional nanostructure, the team observed extremely high levels of selectivity between similar-sized organic compounds that were differentiated by charge. The applications for such selective separations include purifying pharmaceutical ingredients, such as amino acids and antibiotics, and also biofuels-manufacturing processes that use emerging solvents, such as ionic liquids.

Wastewater treatment with peracetic acid

In what is said to be the largest municipal wastewater application using peracetic acid (PAA) disinfectant to date, the Metro Wastewater Reclamation District in Denver, Colo. recently began disinfecting wastewater effluent with a PAA formulation from Enviro Tech Chemical Services, Inc. (Modesto, Calif.; www.envirotech.com) known as Peragreen WW.

PAA is a disinfectant alternative to sodium hypochlorite that allows users to avoid permitting and regulatory issues associated with toxic halogenated byproducts from chlorine-containing disinfectants. While it is more expensive than sodium hypochlorite, PAA is a more potent oxidizer, so it can reduce overall chemical use. Peragreen WW is an equilibrium 15% PAA solution that is stabilized in a proprietary formulation.

The application of PAA is accomplished by metering skids engineered by Stantec Engineering (Edmonton, Alta.; www.stantec.com). The skids contain peristaltic pumps with specially designed tubing made from Teflon and silicone. Enviro Tech installed plastic storage tanks for the PAA system that feature a proprietary medium-density polyethylene liner with high chemical resistance.

The new bulk delivery and dosing system at the Denver wastewater plant has a capacity of more than 30,000 gal of PAA solution. The wastewater treatment system is capable of handling 220 million gal/d with a daily average flow of 146 million gal/d, Enviro Tech says. The company has been supplying the food industry with PAA and other disinfection products since 1991.

A promising catalyst for low-temperature ammonia synthesis

Researchers led by professor Hideo Honoso at Tokyo Institute of Technology (Yokohama City, Japan; www.titech.ac.jp) have discovered a new catalyst that enhances the efficacy of NH_3 synthesis by two orders of magnitude over that of a conventional Ru catalyst at temperatures below 300°C. Furthermore, the developed catalysts are said to be superior to the wüstite-based iron catalyst, which is known as a highly active industrial catalyst at low temperatures and pressures.

The catalyst is composed of self-organized ruthenium-barium core-shell nanoparticles on a mesoporous calcium amide matrix, Ru/Ba-Ca$(NH_2)_2$. To make the catalyst, nanometer-sized Ru–Ba core–shell structures are self-organized onto a Ba-Ca$(NH_2)_2$ support with 3.3-nm dia. during H_2 pretreatment at 500°C. The support material is simultaneously converted into a mesoporous structure with a high surface area (>100 m^2/g), which is higher than 17 m^2/g of the raw Ba-Ca$(NH_2)_2$ support materials. These self-organized nanostructures account for the high catalytic performance in low-temperature NH_3 synthesis.

In laboratory trials, the Ru/Ba-Ca$(NH_2)_2$ catalyst performed NH_3 synthesis with turnover velocity of 7.5 mmol/g·h at 250°C and 9 atm, well above that achieved by industrial iron-based catalysts (2.2 mmol/g·h) and conventional Ru-based (Cs-Ru/MgO) catalyst (0.072 mmol/g·h).

'One-pot' synthesis of conjugated polyenes

The research group of professor Masafumi Hirando at Tokyo University of Agriculture and Technology (TUAT; Koganei City, Japan; www.tuat.ac.jp) has performed the world's first one-pot synthesis of conjugated polyenes, which normally require at least seven steps by conventional methods. This shortens the synthesis time from around a week to as little as 30 minutes. Waste generation is virtually eliminated due to the hydrogen transfer reaction, which enables regio- and stereo-selective reactions for making precursors for electronics chemicals, vitamins and pharmaceuticals.

At room temperature, the new synthesis approach directly produces conjugated tetraenes with 85% yield by reacting 1,3-butadiene over a Ru(0) catalyst containing two internal alkyne ligands. The stoichiometric reaction of [Ru(η^4-cisoid-1,3-butadiene)(η^4-1,5-COD)(NCMe)] with two equivalents of 3-hexyne produces a tetraene complex of Ru(0), [Ru{3–6-η^4-(3E,5E,7E,9E)-4,9-diethyldodeca-3,5,7,9-tetraene}(η^4-1,5-COD)(NCMe)], in 98% yield. When exposed to 1,3-butadiene, the conjugated tetraene ligand is released with 92% yield. The study is described in a recent issue of *Organometallics*.

An explosive way to make porous organic networks

A team from Ulsan National Institute of Science and Technology (Ulsan, South Korea; www.unist.ac.kr), led by professor Jong-Beom Baek has introduced a synthetic methodology for fabricating a three-dimensional porous organic network with a high specific surface area via a solid-state explosion of organic single crystals containing primer molecules. The method involves the Bergman reaction (cyclo-aromatization) of 2,3,6,7, 14, 15-hexaethynyl-9,10-dihydro-9,10-{1,2}benzenoanthracene (HEA), which is a self-polymerizable trifunctional (M3) building block with three enedyne groups (containing a double bond and two triple bonds). X-ray diffraction suggested that two acetone molecules and one water molecule are regularly positioned in the HEA crystal lattice. The acetone and water molecules play a role as primer to trigger explosion. Solid-organic materials can easily melt when heat is applied. However, the newly-developed HEA single crystals trigger explosive Bergman reactions and quickly changes to 3-D porous materials when heat is applied, without the presence of solvents and catalysts.

The polyHEA obtained is a porous material with specific surface area of 1,176 m^2/g displaying unusual sorption capacity for CO_2. The team's method could pave the way for designing and synthesizing molecules suitable for the solid-state formation of other porous organic networks for applications beyond those of liquid-phase processes. ■

SUEZ produces new raw materials and alternative energy from waste, but also from bottom ash. Now, using the internally developed Valomet process, the company will also recover fine, non-ferrous metal particles (up to 20 mm in size) from bottom ash. In November 2015, a pilot project began in Ghent in which metal concentrates from bottom ash were processed and separated. Over a one-year trial period, SUEZ extracted around 1,300 metric tons of fine metal particles, which were then returned to the production process, through foundries and metal refineries. This pilot project recovered aluminum and denser non-ferrous metals, such as copper, lead and zinc.

The new facility, which is expected to be operational by the end of this year, represents a tenfold scaleup, and will have the capacity to process up to 12,000 m.t./yr by 2019. The materials processed will come from European countries, including Belgium, France, the U.K. and Poland.

HANDY ANALYSIS

Researchers at the Fraunhofer Institute for Integrated Circuits (IIS; Erlangen, Germany; www.iis.fraunhofer.de), in cooperation with CapSenze Biosystems AB (Lund, Sweden; www.capsenzw.se) have developed a mobile measuring device that can quickly and reliably detect the presence of biochemical substances in liquids, such as drinking water or juices. The matchbox-sized device, which integrates a biosensor developed by CapSenze and an optimized evaluation circuit from IIS, is able to perform measurements in a couple of minutes, compared to the time-consuming process of sending samples to laboratories for analysis.

Supplying measurement data in the pico- to femtomole (10^{-12} to 10^{-15} mol/L) range, the six different sensors of the biosensor system allow simultaneous detection of six different substances. Different sensor coatings, depending on the substance to be detected, are used to determine the presence of unwanted substances in foodstuffs and animal feed. The biosensor system is a highly sensitive device that can identify, with the corresponding sensor coating, the presence of biochemical substances, such as hormones, pesticides and mycotoxins in extremely low concentrations. ❑

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Plant Watch

Air Liquide inaugurates CO_2-recovery plant in Ontario

February 12, 2018 — Air Liquide Canada, a subsidiary of the Air Liquide Group (Paris, France; www.airliquide.com), inaugurated a carbon dioxide (CO_2) recovery plant in Johnstown, Ontario. The plant is capable of producing over 200 metric tons (m.t.) per day of medical-grade CO_2.

Sabic announces expansion plans in Singapore and the Netherlands

February 12, 2018 — The Saudi Basic Industries Corp. (Sabic; Riyadh; www.sabic.com) plans to increase global capacity for high-performance engineering thermoplastic materials in Asia and the Netherlands. The planned new production facility in Singapore is expected to go online in the first half of 2021. The company also plans to recommission operations at its Bergen op Zoom resin plant in the Netherlands to produce polyphenylene ether in 2019.

KBR awarded contract for new polycarbonate plant in China

February 9, 2018 — KBR, Inc. (Houston; www.kbr.com) will provide proprietary phosgene-based interfacial polycarbonate technology, basic engineering design and proprietary equipment supply to Cangzhou Dahua New Materials Co. (CDNM) for a new 100,000-m.t./yr single-train polycarbonate plant in Cangzhou City, China. CDNM intends to further expand production to 200,000 m.t./yr.

Samsung-CB&I joint venture wins EPC contract for Adnoc refinery upgrade

February 8, 2018 — The Abu Dhabi National Oil Co. (Adnoc; www.adnoc.com) announced that a joint venture (JV) between Samsung Engineering Ltd. (Seoul, South Korea; www.samsungengineering.com) and CB&I (The Woodlands, Tex.; www.cbi.com) was awarded the engineering, procurement and construction (EPC) contract for a $3.1-billion upgrade project at Adnoc's Ruwais petroleum refinery. The refinery modifications, scheduled to be completed by the end of 2022, will enable the Ruwais Refinery-West complex to process up to 420,000 barrels per day (bbl/d) of crude oil.

Henkel begins construction of aerospace materials plant in Spain

February 7, 2018 — Henkel AG & Co. KGaA (Düsseldorf, Germany; www.henkel.com) began construction of a new plant for aerospace materials at its site in Montornès del Vallès, Spain. The facility will include new buildings and equipment for expanded production capacities to support industry trends, such as lightweighting and automation.

Arkema to increase polyamide 12 production in China

February 6, 2018 — Arkema (Colombes, France; www.arkema.com) plans to increase its production capacity for polyamide 12 polymers by 25%. This new capacity will be added at Arkema's Changshu platform in China and is expected to come onstream by mid-2020.

Chandra Asri breaks ground for new polyethylene plant

February 5, 2018 — PT Chandra Asri Petrochemical Tbk (CAP; Jakarta, Indonesia; www.chandra-asri.com) broke ground for a new 400,000-m.t./yr polyethylene (PE) plant in Cilegon, Banten, Indonesia. The total investment cost for the project is estimated to be around $350 million. The completion of the project is scheduled for the end of 2019, with operations commencing in early 2020.

BASF to expand production of alkyl polyglucosides in Ohio and China

February 1, 2018 — BASF SE (Ludwigshafen, Germany; www.basf.com) will increase its global production capacity for alkyl polyglucosides with two production expansion projects at sites in Cincinnati, Ohio, and Jinshan, China. The Cincinnati unit is scheduled to come online in 2018, and the Jinshan unit is planned to start up in 2019.

Air Liquide starts up world-scale oxygen plant at Sasol's Secunda site

February 1, 2018 — Air Liquide started up what is said to be the world's largest oxygen production unit at Sasol Ltd.'s (Johannesburg, South Africa; www.sasol.com) site in Secunda, South Africa. Air Liquide invested around €200 million for the construction of this air separation unit, which has a total production capacity of 5,000 m.t./d of oxygen.

BASF to double MDI production capacity in Geismar

February 1, 2018 — BASF will start the construction of a new methylene diphenyl diisocyanate (MDI) synthesis unit at the company's site in Geismar, La. in the second quarter of 2018. The new plant will double BASF's annual MDI capacity in Geismar from 300,000 m.t./yr to nearly 600,000 m.t./yr.

Solvay to expand production of sodium bicarbonate in Rheinberg

January 31, 2018 — Solvay S.A. (Brussels, Belgium; www.solvay.com) will invest €6 million to expand sodium bicarbonate production capacity at its site in Rheinberg, Germany. Startup of the expanded facility is planned by the end of 2018. Solvay also produces sodium bicarbonate in Torrelavega, Spain.

Mergers & Acquisitions

Aquafil to acquire Invista's Asia Pacific nylon 6 business

February 6, 2018 — Aquafil S.p.A. (Arco, Italy; www.aquafil.com) has signed an agreement with Invista (Wichita, Kan.; www.invista.com) to acquire assets related to Invista's nylon 6 business activities in Asia. The assets to be acquired concern Invista's business for polyamide 6 fiber in the Asia Pacific region, which has a turnover of about $50 million. Closing of the acquisition is expected by the end of March.

Johnson Matthey sells battery systems business to Cummins

January 31, 2018 — Cummins Inc. (Columbus, Ind.; www.cummins.com) acquired Johnson Matthey's (London; www.matthey.com) U.K. automotive-battery systems business, which specializes in high-voltage automotive-grade battery systems. As part of the acquisition, Cummins and Johnson Matthey also agreed to collaborate on the development of high-energy battery materials for commercial applications.

Kaneka acquires Henkel's benzoxazine composites business

January 31, 2018 — Henkel and Kaneka Corp.'s (Tokyo, Japan; www.kaneka.com) wholly owned subsidiary, Kaneka Aerospace, LLC (KAE; San Francisco, Calif.), have finalized the transfer of commercial rights, technologies and patents of Henkel's benzoxazine-based high-performance composites business to KAE. Included in the acquisition are benzoxazine-based prepregs, film adhesives and infusion resins.

Evonik and DSM officially launch Veramaris joint venture

January 30, 2018 — Royal DSM N.V. (Heerlen, the Netherlands; www.dsm.com) and Evonik Industries AG (Essen, Germany; www.evonik.com) have established a new company, Veramaris V.O.F. (www.veramaris.com), for the production of omega-3 fatty acids from natural marine algae. The 50-50 JV is headquartered at the DSM Biotech Campus in Delft, the Netherlands. Veramaris is currently constructing a $200-million production facility in Blair, Nebraska, with commercial production expected to commence in 2019.

Sabic acquires 24.99% stake in Clariant

January 25, 2018 — Sabic has acquired a 24.99% stake in Clariant (Muttenz, Switzerland: www.clariant.com). This acquisition makes Sabic the largest Clariant shareholder. Sabic is currently a partner of Clariant in the U.S.-based catalyst JV Scientific Design Company, Inc.

Mexichem acquires Pennsylvania-based specialty PVC producer

January 23, 2018 — Mexichem S.A.B. de C.V. (Tlalnepantla, Mexico; www.mexichem.com) has acquired Sylvin Technologies Inc., a specialty polyvinyl chloride (PVC) compounds manufacturer based in Denver, Pa., for an enterprise value of $39 million. Mexichem will consolidate Sylvin under the company's Vinyl business group as part of its Compounds business unit. ■

Mary Page Bailey

Solar Chemistry Heats Up

Major efforts are underway to develop new process technology for making chemicals using sunlight and the products of combustion

No one can deny that the sun provides more than enough energy to supply the world's energy and materials needs. After all, Mother Nature has been using sunlight for millennia, making a myriad of chemicals from carbon dioxide and water via photosynthesis. And the fact is, fossil fuels are the remnants of sun-to-chemical production, which humans have been exploiting for the last few centuries as alternatives to the biomass that our ancestors used for cooking and heating needs.

As the energy demands of the human species continue to grow, due to both population growth and usage, it doesn't take more than a back-of-the-envelope calculation to show that eventually, our reliance on fossil fuels will come to an end — it's simply a question of when. After all, there is only a finite amount of coal, gas and petroleum. And in the last few decades, most of the conscientious scientific and industrial community have realized that something needs to be done to slow down the release of CO_2 into the atmosphere.

Planning for future generations, efforts around the world are growing to ween our current dependence on fossil resources by taking advantage of the ever-present sunshine flooding some part of the planet every day. Although the energy sector tends to receive the most headline-grabbing attention about solar power, there is another less well known, but very active pursuit for using sunlight, CO_2 and water for manufacturing chemicals (Figure 1). This article is a modest attempt to highlight some of these activities, which are making progress towards the production of renewable H_2 and synthesis gas (syngas; H_2 and CO), which is then used for making ammonia, liquid fuels, alcohols and more (see Table 1; a more comprehensive table can be found in the online version of this article at www.chemengonline.com).

DLR

FIGURE 1. In order to accelerate the design of reactors for performing solar chemistry, solar simulators are being used. Simulators enable scientists to work during cloudy days or at night, and avoid the costly infrastructure needed for solar towers. Shown here is DLR's Synlight — the world's largest solar simulator — that started operating last March in Jülich, Germany

Understand the limits

When it comes to making chemicals from CO_2, water and sunlight, there are basically three possibilities, explains Christian Sattler, head of solar chemical engineering at the German Aerospace Center (DLR; Cologne, Germany; www.dlr.de). Sunlight can be used as photons for photosynthesis; it can be transformed in photovoltaic (PV) cells into electrons, and then used in electrochemical processes; or it could be used as heat in thermochemical processes. "There is no contradiction, but actually a synergy between the different routes," says Sattler, adding that "this is the reason why we have a very successful joint solar-fuels topic in the Helmholtz Renewable Energy program [www.helmholtz.de] between the three routes."

For industrial applications, a basic principle needs to be taken into account seriously, Sattler continues: "Solar radiation is a rather diluted energy source, whereas the produced fuels or chemicals have a very high energy density. Therefore, from a chemical point of view, if sunlight is not concentrated to higher energy densities, the amount of product per irradiated reactor surface is limited to far less than 1 kW/m^2. This amount of energy is not available for photochemical processes, but only a fraction of it with the right wavelengths and it has to be multiplied with the efficiency of the chemical process, which gives a rather low number. Therefore, from a large-scale industrial point of view, it makes sense to concentrate solar radiation — either in the form of heat or of electricity — to use it in chemical processes. This makes compact reactors with high throughput possible," he says.

Splitting water

The electrolysis of water into H_2 and O_2 has been used industrially for many years, especially in regions of the world where electricity has been inexpensive (such as that from nuclear or hydroelectric plants). Now, as the cost of PV technology has dropped, solar-based renewable H_2 production is making its way into the chemical process industries (CPI), including petroleum refineries. In January, for example, Royal Dutch Shell Plc (The Hague, the Netherlands; www.shell.com) and ITM Power (Sheffield, U.K.; www.itm-power.com) announced plans to build the

world's largest water-electrolysis plant to produce H_2 for use in Shell's Rheinland Refinery in Wessling, Germany. When the 10-MW "Refhyne" plant starts up in 2020, it will produce 1,300 metric ton (m.t.) per year of H_2 using renewable electricity.

Meanwhile, there is an ongoing effort to develop alternative methods of making H_2 from water, by so-called advanced water-splitting (AWS) technologies. One (of many) such initiatives is the HydroGEN Energy Materials Network (EMN) consortium (www.h2awsm.org), which is led by the U.S. Dept. of Energy's (DOE; Washington, D.C.; www.energy.gov) National Renewable Energy Laboratory (Golden, Colo.; www.nrel.gov), and includes the Lawrence Berkeley National Laboratory (Calif.; www.lbl.gov), Sandia National Laboratories (Livermore, Calif.; www.sandia.gov), Lawrence Livermore National Laboratory (Calif.; www.llnl.gov) and Savanna River National Laboratory (Jackson, S.C.; www.srnl.doe.gov). Among the AWS technologies under investigation are low-temperature anion-exchange membrane (AEM) and proton-exchange membrane (PEM) electrolysis, high-temperature electrolysis, photoelectrochemical (PEC) pathways and solar thermochemical (STCH) water splitting.

Last November, Proton OnSite (Wallingford, Conn.; www.protononsite.com) received around \$1.8 million in a cooperative agreement award to lead the DOE's AWS Benchmarking Project with the HydroGEN EMN consortium. The goal is to speed the discovery and development of efficient, durable and low-cost AWS materials capable of meeting DOE's long-term H_2-production goal of less than \$2/kg.

Looking at STCH, for example, the Fuel Cell Technologies Office withinDOE (https://energy.gov/eere/fuelcells/fuel-cell-technologies-office) has funded Sandia National Laboratories for many years to verify the potential for solar-thermochemical cycles for H_2 production to be commercially viable, and to advance STCH's technology readiness level through R&D efforts focused on materials and reactor design, says project lead Anthony McDaniel at Sandia. "Two-step, non-volatile metal-oxide cycles are currently the thermochemistry of choice. Together with DLR (a subcontractor to Sandia on one particular project), the team developed a 3-kW_{th}-scaled prototype and successfully demonstrated Sandia's moving particle bed, solar-thermochemical reactor technology," says McDaniel.

"The project with DLR [called HEST-HY in Table 1] was comprised of three main tasks: discovery of redox active materials; reactor prototype design and demonstration; and building a high-fidelity model to predict performance of a large-scale plant (targeting 100 kg/d H_2 production)," explains McDaniel. "And while the optimal material still eludes us, the project did complete

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Astor: Automized thermochemical water splitting (2017–2020)	Rheinische Fachhochschule Köln, Stausberg & Vosding GmbH, AWS-Technik e.K.	Using solar-thermal energy (at 800–1,400°C) to make H_2 from reaction of water with metal oxides	Demonstration plant for the "Synlight" (Figure 1) will be built at the DLR site in Jülich	EFRE NRW
Sun-to-Liquid (2016–2019)	Bauhaus Luftfahrt, ETH Zurich, IMDEA Energy, Hygear B.V., Abengoa S.A., Arttic	Synthesize liquid hydrocarbons from H_2O and CO_2, via formation of syngas and subsequent Fischer-Tropsch (F-T) synthesis	High-flux solar-concentrating subsystem constructed at IMDEA Energia in Madrid, Spain	E.U.'s Horizon 2020 Framework Program
Hydrosol: Solar thermochemical water splitting (2014–2017)	CIEMAT, Hygear B.V., Hellenic Petroleum, APTL	Using solar-thermal energy (at 800–1,400°C) to make H_2 from reaction of water with metal oxides	Three reactors have been built, each with a thermal capacity of 250 kW	E.U.'s Horizon 2020 Framework Program
Sophia: Solar integrated pressurized high-temperature electrolysis (HTE) (2014–2017)	CEA, HyGear B.V., VTT, Engie, HTceramix S.A., SolidPower	Decomposition of steam by a combination of electrical and high-temperature (700–800°C) heat into carbon-free H_2 and O_2	A 3-kW_e pressurized HTE was designed, built and operated	European Commission (FCH-JU)
Solpart: High-temperature solar-heated reactors for industrial production of reactive particles (2016–2020)	CNRS, Cemex, Abengoa Research, University of Manchester, EPPT, comessa, eurovia, New Lime Development, Université Cadi Ayyad, OPC	To utilize solar-thermal energy to perform the calcination step used in the lime, phosphate and cement industries	Technology has the potential to save two thirds of the energy requirements needed by conventional calcination processes	E.U.'s Horizon 2020 Framework Program
Pegasus: Renewable power generation by solar-particle-receiver-driven sulfur-storage cycle (2016–2020)	APTL/Certh, Karlsruhe Institute of Technology, Baltic Ceramics, Processi Innovativi	Using sulfur to store energy in an S-SO_2-H_2SO_4 cycle (for more information, see *Chem. Eng.*, June 2017, p. 10)	Demonstration operation of an integrated pilot unit is planned for the last project year at the DLR Jülich Solar Power Tower facility	INEA (European Commission) and Horizon 2020 Framework Program
Düsol: Sustainable fertilizer production from sun, air and water (2016–2019)	GTT Gesellschaft für Technische Thermochemie- und physik mbH, aixprocess GmbH	Making nitrogen fertilizers via a Haber-Bosch process in which the H_2 is derived from water splitting, and the N_2 from a solar-thermochemical air-separation process	Emphasis will be placed on the thermochemical air-separation process for producing N_2	EFRE.NRW
Solam: Solar aluminum smelting (2015–2018)	aixprocess GmbH, CSIR, NFTN, Eskom, DST (last four South African)	An effort to decarbonize the aluminum smelting process using solar-thermal energy	A solar-powered pilot-scale rotary kiln built and tested	German Federal Ministry of Education and Research (BMBF)
Virtual Institute SolarSynGas: Thermochemical research for CO_2-neutral renewable fuels (2012–2017)	ETH Zurich, Karlsruhe Institute of Technology, Technical University of Clausthal	To produce CO_2-neutral fuels via a thermochemical route	One focus was to develop metal-oxide-based redox materials for the production of H_2, and then make fuels from water and CO_2	Inniative and Networking Fund, Helmholtz Assn. of German Research Centers
HEST-HY: High efficiency solar-thermal hydrogen (2014–2017)	Sandia National Laboratories, Colorado School of Mines, Northwestern University, Stanford University, Bucknell University, Arizona State University	To develop new methods and reactors for operating thermochemical looping cycles to make H_2 by splitting	Part of DOE-funded STCH (solar thermochemical hydrogen) project at Sandia. Negotiations are underway for follow-up project	U.S. Dept. of Energy

*Source: DLR, Institute of Solar Research; DLR is a partner in all projects listed. A more comprehensive table can be found online at www.chemengonline.com

prototype construction and accomplish the demonstration," he adds. The high-fidelity plant model is currently being used to conduct detailed technoeconomic studies of the STCH process. Regarding the moving particle-bed reactor, McDaniel says that Sandia's concepts embodies spatial and temporal separation of pressure, temperature and reaction products, as well as continuous on-sun operation. "These design attributes are a significant departure from the traditional norms of this technology development community and key to high efficiency operation," he says. Although this specific project was completed last year, the materials work continues through the DOE-funded HydroGEN consortium.

That said, a key metric that drives the development of PEC and STCH is the solar-to-H_2 conversion efficiency — "essentially challenging ourselves to dramatically outdo Mother Nature, and in fact, outdo a conventional electrolyzer (~10% solar-to-H_2 efficiency when coupled to a Si-based PV system)," says McDaniel.

"On paper, PEC and STCH promise to dramatically increase the system efficiency (DOE technology development targets >25%)," McDaniel continues. "I favor the STCH approach because it has the theoretical potential to achieve a high solar-to-fuel conversion efficiency. Concentrated solar utilizes the full spectrum (not selectively absorbing photosystems) and converts thermal energy directly into fuel (that is, a reduced oxide) without incurring serial inefficiencies associated with the photon-to-electron intermediate step."

"In comparing PEC to STCH from a technology development perspective, they each face different challenges," says McDaniel. The best PEC chip ever devised so far operates at ~16% solar-to-fuel conversion efficiency. But, McDainel points out, it is a small device, producing a few Watts of H_2, that degrades rapidly. The largest STCH process demonstrated is 100 kW (with 750 kW in the Hydrosol Plant endeavor, described below), and operates continuously for weeks — but at a much lower solar-to-fuel conversion efficiency. The highest STCH process efficiency demonstrated thus far is 5.25% at 4 kW. "So, PEC wins on demonstrated efficiency and STCH wins on demonstrated scalability. At the moment, DOE is betting on both," McDaniel says.

Meanwhile, the Hydrosol Plant project started up last November at CIEMAT's (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas; www.ciemat.es) Plataforma Solar de Almería (PSA) in southern Spain to become the world's largest solar-chemical installation for producing H_2. The plant is the culmination of an international project coordinated by the Greek Aerosol and Particle Technology Laboratory, in collaboration with Germany's DLR, Spanish CIEMAT, the Dutch company HyGear, and the Greek energy-supply company Hellenic Petroleum. DLR is predominantly responsible for the development of the reactor, which uses solar-thermal energy to make H_2 by the reaction of H_2O with metal oxides at temperatures of 800–1,400°C. "This is not a laboratory experiment anymore, but it is also no industrial demonstration," says DLR's Sattler. "The next step will be to further scale it up into the megawatt range, which will be expensive," he adds.

ETH Zurich/Solar-Jet

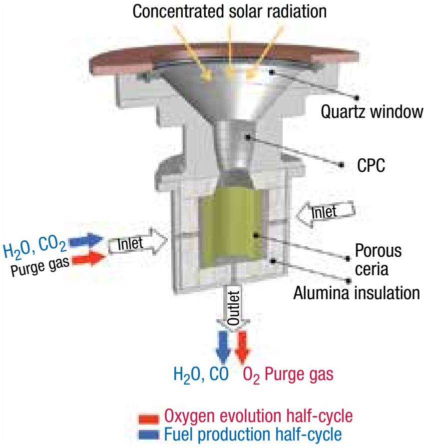

FIGURE 2. As part of the Solar-Jet project, this solar-thermochemical reactor developed at ETH Zurich, sucessfully demonstrated the ability to produce syngas, from which kerosene (jet fuel) was made via F-T synthesis

Solar-thermochemical syngas

While H_2 is an important chemical in itself, as well as an energy carrier that can be, and increasingly is being used to power fuel-cell driven vehicles, syngas is the key building block when it comes to producing basic chemicals. And this is an area where the power of the sun is literally heating up interest. In addition to the Hydrosol projects, DLR is active in a number of projects aimed at producing syngas, fuels and other chemicals by solar-thermochemical

ARTIFICIAL PHOTOSYNTHESIS

In January, Siemens AG (Munich; www.siemens.com) and Evonik Industries AG (Essen, both Germany; www.evonik.com) started the Rheticus project — a two-year project to use electricity from renewable sources and bacteria to convert CO_2 and water into specialty chemicals, such as butanol and hexanol. With €2.8 million funding from the Federal Ministry of Education and Research (BMBF; Bonn and Berlin, Germany; www.bmbf.de), the companies plan to bring a test plant onstream by 2021 at Evonik's site in Marl, Germany. After that, the next step could be a plant with a production capacity of 20,000 m.t./yr, says Evonik.

In the Rheticus project, syngas will be produced electrolytically (using electricity generated by renewable sources, such as photovoltaic (PV) cells or wind generators) by the reduction of CO_2 into syngas at the cathode, while water is split into O_2 and H^+ ions at the anode. The syngas will then be fermented into alcohols using aerobic microorganisms. The complete process has been demonstrated at small scale, as described in a *Nature Catalysis* article published in January. In that study, a PV module supplied the electricity (480 mA per 10 cm^2 at 3.7 V) operating at 11% conversion efficiency. The electrolyzer used a commercial Ag-based gas-diffusion electrode (GDE) from Covestro AG (Leverkusen, Germany; www.coversto.com) for the cathode, and an indium/mixed-metal-oxide-coated titanium plate from ElectroCell A/S (Tarm, Denmark; www.electrocell.com) for the anode. When coupled to a fermentation module, the syngas from the electrolyzer is metabolized into butanol and hexanol with high carbon selectivity. The study demonstrated that the conversion of PV electricity, CO_2 and water to the desired alcohols achieved close to 100% Faradic efficiency. Evonik says that artificial photosynthesis is closer than expected with this scalable hybrid system.

Meanwhile, researchers around the world are regularly reporting new "breakthroughs" in catalyst development targeting the steps of artificial photosynthesis — either H_2 production or CO_2 reduction, or both simultaneously. These efforts are often reported in the Chementator pages of this magazine. For example, researchers from the National University of Singapore (www.nus.edu.sg) have developed a prototype device that uses artificial photosynthesis to produce ethylene using only sunlight, water and CO_2, at room temperature and pressure (*Chem. Eng.*, January 2018, p. 7). Another example can be found in this month's Chementator Briefs on p. 8, which mentions the findings of a recent study for making solar H_2 in an international colaboration led by the University of Twente's MESA+ Institute.

Meanwhile, progress continues at the Joint Center for Artificial Photosysthesis (JCAP; www.solarfuelshub.org), which was established in 2010 by the DOE, and is the U.S.'s largest research program dedicated to advance artificial-fuels generation science and technology. The second phase of this program started in 2015, with the focus on solar CO_2-reduction to fuels. JCAP is led by the California Institute of Technology (Pasadena; www.caltech.edu), in partnership with the Lawrence Berkeley National Laboratory. Other partners include the University of California at Irvine and San Diego, and the SLAC National Accelerator Laboratory, operated by Stanford University. ❑

methods (Table 1). "Some of these are far beyond laboratory scale," says Sattler.

For example, as part of the Sun-to-Liquid project (www.sun-to-liquid.eu), a small solar tower system was built at IMDEA Energía at Móstoles Technology Park, near Madrid, in 2016. This high-flux solar-concentrating subsystem consists of an ultra-modular solar heliostat central receiver that provides intense solar radiation for high-temperature applications beyond the capabilities of current commercial concentrated solar power (CSP) installations. The heliostat field consists of 169 small size heliostats (1.9 m × 1.6 m). When all heliostats are aligned, it is possible to fulfil the specified flux above 2,500 kW/m^2 for at least 50 kW and an aperture of 16 cm, with a peak flux of 3,000 kW/m^2. A reliable roadmap for competitive drop-in fuel production from water, carbon dioxide and solar energy will be established in the project.

The E.U.-funded Sun-to-Liquid project is the followup to a predecessor project, Solar-Jet, in which a solar reactor developed at ETH Zurich (Switzerland; www.prec.ethz.ch) was successfully operated for splitting H_2O and CO_2 to produce syngas, which was subsequently converted via Fischer-Tropsch (F-T) synthesis into kerosene.

"In the framework of the Solar-Jet project, we have experimentally demonstrated at laboratory-scale the entire production chain to renewable jet fuel (kerosene) via solar thermochemical splitting of water and CO_2," says Philipp Furler, a research associate at ETH Zurich and operating agent for solar chemistry research of the International Energy Agency's (Paris, France; www.iea.org) technology program, SolarPACES. "If coupled to CO_2-capture from atmospheric air, such kerosene has zero net CO_2 emissions and can be certified for commercial aviation by minor addendum to the existing D7566 specification for synthesized hydrocarbons. Furthermore, we boosted the reactor energy-conversion efficiency by a factor of 13 to a record 5.25%. Within Sun-to-Liquid, we are now scaling up the process to a solar-tower," says Furler.

In parallel, Sunredox — a spinoff company of ETH Zurich — jointly with Synhelion (Switzerland; www.synhelion.com) and Eni S.p.A (Rome, Italy; www.eni.com) are working in close collaboration to further develop and scale-up the solar chemical technology to the megawatt size over the next years, with the goal of reaching solar-to-fuel energy conversion efficiencies beyond 20% for securing economic competitiveness, says Furler, the co-founder and CEO of Sunredox. ENI and Synhelion signed a cooperation agreement in June 2017 for this purpose. "We are targeting the first 20-MW pilot plant by 2023 and the commercial phase by 2025," he says.

Furler points out three main advantages of the thermochemical route to renewable fuels compared to alternative approaches. Firstly, the thermochemical route uses the entire solar spectrum and bypasses critical energy conversion stages, such as electricity generation, electrolysis, or reverse-water-gas-shift and thus can exceed the energy conversion efficiencies of alternative processes and become cheaper. Secondly, it is applied in desert regions with high direct normal irradiance (DNI), whereas fuels derived from biomass use valuable agricultural land and suffer from low energy-conversion efficiencies (typically below 1%) resulting in critical land footprint. Thirdly, it can be combined with inexpensive thermal-energy storage solutions, such as a packed bed of rocks ($15/kWh), to enable continuous and uninterrupted 24/7 operation of the plant, regardless of the sunlight intermittency. In contrast, approaches based on electricity lack inexpensive storage solutions, says Furler. ■

Gerald Ondrey

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Solam: Solar aluminum smelting (2015–2018)	DLR, aixprocess GmbH, CSIR, NFTN, Eskom, DST (last four South African)	An effort to decarbonize the aluminum smelting process using solar-thermal energy	A solar-powered pilot-scale rotary kiln built and tested	German Federal Ministry of Education and Research (BMBF)
Virtual Institute SolarSynGas: Thermochemical research for CO_2-neutral renewable fuels (2012–2017)	DLR, ETH Zurich, Karlsruhe Institute of Technology, Technical University of Clausthal	To produce CO_2-neutral fuels via a thermochemical route	One focus was to develop metal-oxide-based redox materials for the production of H_2, and then make fuels from water and CO_2	Inniative and Networking Fund, Helmholtz Assn. of German Research Centers
HEST-HY: High efficiency solar-thermal hydrogen (2014–2017)	Sandia National Laboratories, Colorado School of Mines, Northwestern University, Stanford University, Bucknell University, Arizona State University, DLR	To develop new methods and reactors for operating thermochemical looping cycles to make H_2 by splitting	Part of DOE-funded STCH (solar thermochemical hydrogen) project at Sandia. Negotiations are underway for follow-up project	U.S. Dept. of Energy
SynENI (2017-2020)	ENI S.p.A, Synhelion SA, Sunredox LLC, ETH Zurich	Development of a continuous redox process that converts CO_2/H_2O into syngas using solar energy	Scale up to megawatt size through the construction of several pilot plants	ENI S.p.A, Synhelion SA
CST Bayer Alumina Process (2017-2021)	The University of Adelaide, CSIRO, Alcoa, Hatch, ITP, UNSW	Enable 29–45% solar share with minimal disruption to the current refinery process	Integrating low and high temperature CST, solar reforming and energy storage into the energy-intensive Bayer alumina process	ARENA (Australian Renewable Energy Agency)
ASTRI Node 4 (P42) (2013-2020)	The University of Adelaide, ANU, CSIRO, Flinders University, Arizona State University (ASU), University of Colorado Boulder, ETH Zurich	Creat new CST markets through solar fuels and lower cost & de-risk technology for long-term sustainable feed-stock	Assessment and development of short and long-term pathways for solar fuels ranging from solar reforming of natural gas to pure H_2O/CO_2 splitting cycles	ARENA
Particle Reactor for water splitting (2017-2019)	Niigata University, University of Miyazaki, Mitaka Kohki Co. Ltd	Development of a 100-kW_{th} particle fluidized-bed reactor for two-step water splitting	Experiments on a 100-kW solar beam-down concentrator at the University of Miyazaki (Japan)	Niigata University, University of Miyazaki, Mitaka Kohki Co. Ltd
Solar Natural Gas Steam Reforming (2016-2020)	USP-SISEA (Laboratorio de Sistemas Energeticos Alternativos) Brazil	Development and testing of lab-scale reactor prototypes for solar steam reforming of natural gas	Experiments on a 10–20-kW solar simulator	RCGI (Research Centre for Gas Innovations), FAPESP (Sao Paulo State), Shell
Solar hydrothermal conversion of biomass (2016-2019)	ENEA, University of Palermo	Integration of solar heat into hydrothermal biomass conversion process using molten salts as HTF	Experimental and conceptual studies	ENEA, University of Palermo
Source: DLR Institute of Solar Research (Germany) and ETH Zurich (Switzerland)				

Clearing the Air

Modern air-filtration systems provide more-efficient dust collection and assist with air quality compliance

Air-filtration and dust-collection systems are the go-to gear for protecting employees and equipment from dust exposure and for complying with air-quality, safety and combustible-dust regulations enforced by local, state and federal authorities. Despite the necessity of the equipment, many processors use legacy systems that no longer function at the highest levels of filtration or energy efficiency or, worse, do not meet National Fire Protection Agency (NFPA; Quincy, Mass.; www.nfpa.org) guidelines for combustible dusts. Clearly, these are very big concerns in chemical process industries (CPI). For this reason, updating to more modern equipment may be in order. However, because every dust, every facility and every process is different, there's a lot to consider when evaluating a new dust collection system.

Donaldson

FIGURE 1. The Downflo Evolution (DFE) combines the latest in filtration technologies in a dust collector that allows utilization of a variety of mitigation equipment strategies

The necessity of air filtration

"Most of the systems we sell are related to improving air quality and protecting employees from exposure to contaminated air or direct exposure to the contaminant being collected," says Travis Haynam with Parker Hannifin's Industrial Gas and Filtration Division (Lancaster, N.Y.; www.parker.com). "Asset protection — protecting process equipment from dust that may cause corrosion or get inside bearings or moving parts of the machinery and cause abnormal wear or premature failure — is another factor in employing a dust collection system. And, certainly, a lot of the material chemical processors work with presents a risk of explosion or combustibility, so collecting and controlling combustible dust helps protect from these hazards," Haynam says.

While air-filtration and dust-collection systems are nothing new for chemical processors, problems arise when existing equipment can no longer keep up with current standards or processes. "There are two issues we often see. First, a lot of facilities have legacy systems that aren't properly protected according to current NFPA standards, which is a problem in the chemical industry because they often handle more exotic dusts with higher explosivity ratings," says Steve McConnell, global director of filtration with Schenck Process (Kansas City, Mo.; www.schenckprocess.com).

"The second issue is that a lot of legacy systems have gone out of balance due to changes in the process or the addition of new ductwork and pick-up points. The system was likely designed and working correctly initially, but alterations may cause the collection system to become problematic in that it is no longer collecting the dust in an efficient manner."

Upgrading the system may seem like an obvious step, but experts say selecting air-filtration equipment is anything but simple. For this reason, many equipment providers, including Schenck, have engineering groups that will assist processors in determining what they need to protect employees and facilities from dust. "Our dust-collection engineering group includes industrial ventilation design specialists with experience in ductwork de-

IN BRIEF

THE NECESSITY OF AIR FILTRATION

HANDLING COMBUSTIBLE DUSTS

REDUCING OPERATING COSTS

Camfil

FIGURE 2. V-Bank style filters, such as Camfil's Durafil ES, are excellent for systems with varying or low airflow, have high dirt-loading capacity for long life and are available in efficiencies of MERV 11, 13 and 14, or ePM2.5 and ePM1

Schenck

FIGURE 3. To reduce energy usage, Schenck offers its MCF PowerSaver dust collector, which can save up to 50% of operational costs by using medium-pressure air for the cleaning cycle

sign and dust collection systems," says McConnell. "They analyze the health of existing systems, look at maintenance schedules, provide a complete ductwork and airflow design analysis and offer recommendations for existing systems that aren't working properly and aren't NFPA compliant, as well as for upfront design of new systems."

Experts agree that having this type of engineering study is necessary to find the system that will work most efficiently and meet the specific dust collection needs of each facility. And, the two most-asked questions during these studies are how to handle combustible dusts and how to lower the overall cost of the system while providing the most efficient filtration.

Handling combustible dusts

Combustible dusts have become one of the biggest concerns for industry over the last few years due to some large, dust-related explosions. These incidents have spurred initiatives such as the Occupational Safety and Health Administration's (OSHA; Washington, D.C.; www.osha.gov) 2008 Combustible Dust National Emphasis Program; and NFPA's recent 652 Standard on the Fundamentals of Combustible Dust (2016 edition). While the NFPA standards aren't necessarily law, they can be enforced as such on a regional basis, if adopted. NFPA 652 was developed to promote hazard analysis, awareness, prevention and protection, but because the hazard-analysis portion of the standard is new and because prevention and protection can take different forms for each facility, many processors aren't sure what equipment they need to keep employees and facilities safe.

"Our customers ask for the 'easy button' solution, but the challenge with combustible dusts is that there is no 'easy button,'" says Karen Wear, market manager with Donaldson (Bloomington, Minn.; www.donaldson.com). "Each processor needs to work through individual needs and hazards to find a solution to the combustible dust issue that best works for them."

In a nutshell, NFPA 652 requires a dust hazard analysis and risk assessment for each process that handles or creates combustible dust for both new and existing installations by October 2018. Following analysis that determines where combustible dust is an issue, mitigation of, and protection from, hazards becomes necessary.

"We are not experts on combustible dust mitigation, but we can help customers through the process of determining what they may need. To better explain what is necessary, we created a Combustible Dust Roadmap that guides users through the process of determining which type of collection, mitigation and protection equipment they may want to consider," says Wear (this Roadmap can be found at the end of the online version of this article at www.chemengonline.com). "The first step in the process is the dust hazard analysis. For any facility with dust, they need to determine any risks associated with their dust, such as whether the dust is explosive, flammable or toxic, and if it has the potential to cause a reaction if combined with another type of dust. This typically requires sending dusts out for testing. If it is determined that a dust is combustible or explosive, further testing is needed to determine the explosibility severity and other factors. Understanding these parameters can then guide processors in the selection of dust collection and the necessary mitigation and protection equipment."

If combustible dust is found to be an issue, selection of equipment, says Wear, should include options for mitigation and protection for both fire and explosion risks. Mitigation refers to equipment that helps reduce the potential for a fire or explosion from occurring and protection refers to equipment that reduces the damage risks to employees, equipment and the facility, if an event does occur.

Mitigation and prevention equipment might include spark arrestors or spark-abatement systems that would detect and douse a spark with fluid, or inerting systems that would blanket the spark with a material to inert the spark before a fire could take place in the collector.

Protection equipment usually includes technologies that minimize the effects if an event does occur,

such as isolation systems, fire suppression systems and explosion vents or explosion suppression systems. Location of the dust collection system — whether it is indoors or out — is also a factor in selecting mitigation equipment.

While combustible dust hasn't created major changes in dust-collector design, it has made users aware that the dust collector is not the only piece of equipment they need to consider. "Customers realize they can't just buy a new base-level dust collector and meet the requirements for combustible dust," says Wear. "Additional equipment may be needed to meet the mitigation strategy they have mapped out."

However, having a base technology that can support combustible dust equipment options is a must. For this reason, Donaldson offers its Downflo Evolution (DFE) dust collector (Figure 1). "The DFE provides a combination of the latest in filtration technology in a dust collector that allows utilization of a variety of mitigation equipment strategies," notes Wear. "The filtration technology is important because it must be as effective as possible in removing the dust from the airstream, especially when collecting toxic or reactive dusts, while at the same time allowing the majority of available mitigation options to be applied."

Wear stresses that it is important to work with a knowledgeable employee safety and health professional and an industrial ventilation designer who understand the applicable standards and regulations, as well as the unique process and facility requirements, to ensure nuisance dusts are managed safely and effectively.

Reducing operating costs

Not only does dust-collection equipment cost money upfront, but air-filtration systems are notoriously expensive to operate and maintain. Experts suggest seeking out modern technologies that work toward reducing these costs via greater energy and filtration efficiencies and increased reliability.

"After the basics of how to capture the particle, keep it captured and dispose of it, as well as meeting any combustible-dust standards, comes the important issue of total cost of ownership," says Greg Carmichael, vice president of sales with RoboVent (Sterling Heights, Mich.; www.robovent.com). "Energy efficiency, filter life and maintenance costs all factor in here and they are often all tied together."

For example, filters that last longer in the system typically use less energy, says Charlie Seyffer, manager of technical materials with Camfil USA (Riverdale, N.J.; www.camfil.us). "One of the biggest expenses is having to change filters. Not only is there the cost of purchasing new filters, but there is also a cost associated with the labor, so longer-lasting filters are usually in demand. Also important is the amount of energy a filter will use."

To meet these needs, filter manufacturers work toward configuring filters to keep resistance down and

Parker Hannifin

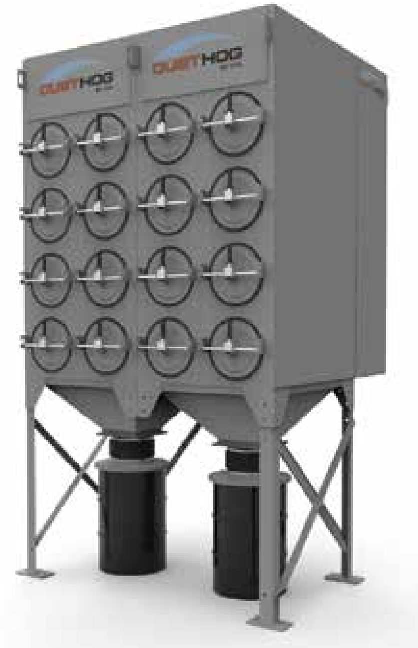


FIGURE 4. Parker's DustHog SFC dust collection units employ a pulse cleaning technology that "pulses off" dust from the filter

RoboVent

FIGURE 5. RoboVent's eTell Intelligent Controls eliminate maintenance efforts where they aren't needed and help processors move toward predictive maintenance

provide increased media area for longer life, he says. Camfil offers Hi-Flo ES filters, which use 27 to 50% less energy than competitive filters and offer 25 to 50% longer life compared to competitive rigid filters. These high-efficiency pocket filters offer a unique configuration and high-loft, air-laid microfiber glass media for optimal performance. Small fiber diameter and uniform lofting provide uniform capture of submicron particles and low resistance to airflow, which increases energy efficiency.

The company's Durafil ES provides an "energy-optimized" filter design that makes it possible to save 30 to 40% more energy than standard V-shaped filters and 30 to 50% versus other final-filter-product designs. The curved form of the air inlet and outlet provides greater open area than other V-shaped filters, resulting in a lower pressure-drop profile. In addition, the media packs use a newly developed height-to-pleat spacing ratio that works in conjunction with the radial inlet and outlet to minimize pressure drop. The pleat separators ensure plated stability to provide continual low-energy usage performance. And, the Energy Saver media is designed with a fiber structure that maximizes filter life (Figure 2).

The method by which the collector cleans the filter is another factor affecting energy efficiency. Schenck's McConnell says: "Dust collectors usually use compressed air to clean the filters, which is a notorious energy hog." To reduce energy usage, Schenck offers its MCF PowerSaver dust collector, which can save up to 50% of operational costs by using medium-pressure air for the cleaning cycle (Figure 3). The integrated blower provides the 0.49 bar, medium-pressure air for cleaning, which eliminates the need for plant compressed air in the filter. "Having its own positive-displacement blower supply cleaning air boosts energy efficiency because you are using less horsepower for cleaning cycles," he explains.

Parker is also changing up the way filters are cleaned in an effort to reduce energy usage. The company's DustHog SFC dust collection units employ a pulse-cleaning technology that "pulses off" dust from the filter (Figure 4). Using an optimized nozzle and venturi, air is pulsed at a precisely calculated distance through an unobstructed airway. The result is increased pulse-cleaning energy with lower pressure drop and longer cartridge life. Because fewer pulses are needed to clean the filters, less compressed air is used and filter life is increased because there is less stress on the filter media.

In addition to extending filter life and reducing energy costs, better management of maintenance activities is another way to lower the total cost of ownership, explains RoboVent's Carmichael. Smart controls and the emerging industrial internet of things (IIoT) are helping to accomplish that. RoboVent's eTell Intelligent Controls eliminate maintenance efforts where they aren't needed and help processors move toward predictive maintenance (Figure 5). The control system predicts how much life is left in filters and when tasks should be performed based on system use patterns. An available cloud-based application provides visibility for all dust collection equipment within multiple facilities or on a single application. And, eTell is able to learn the system and the processes and make realtime adjustments to save energy and extend filter life.

While air-filtration and dust-collection systems are often viewed as necessary operating expenses, updating them to meet current standards and enhance energy efficiency while reducing operating costs can provide financial benefits, says Parker's Haynam. "If the current system is causing problems, replacing it will provide payback through energy savings, reduced risk or less maintenance," he says. "In addition to those benefits, there is the benefit of having a cleaner facility, which will improve the process as well as employee health and wellness." ■

Joy LePree

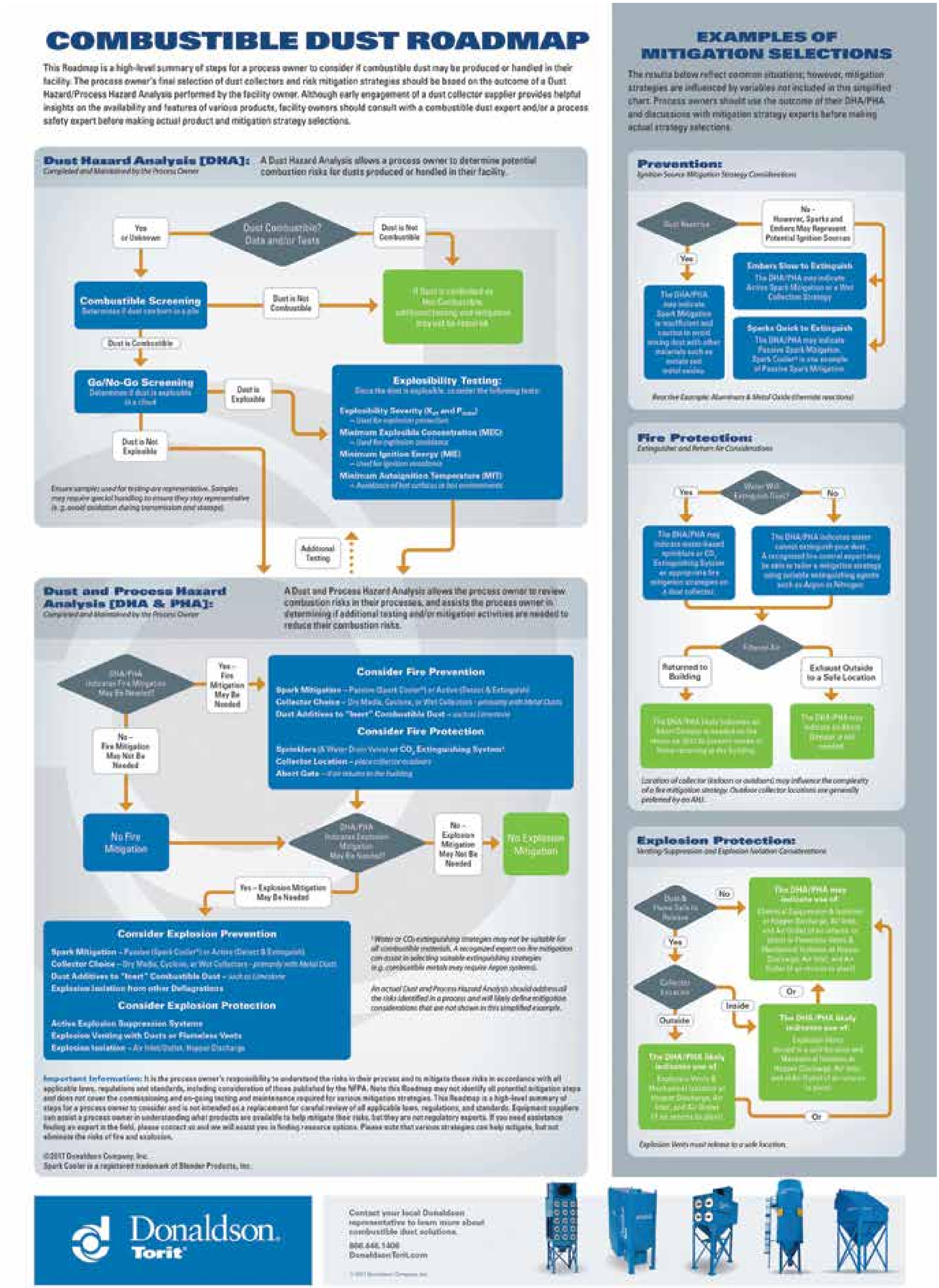


FIGURE 1. Donaldson's Combustible Dust Roadmap guides users through the process of determining which type of collection, mitigation and protection equipment they may want to consider

Process Control Hardware

Wired network bridge enables remote troubleshooting

This company has added the PLX35-NB2 Network Bridge to its slate of Secure Remote Access solutions. This wired solution can help system integrators, machine builders, or anyone who wants to cut down on unnecessary travel time for minor fixes by allowing them to troubleshoot their remote equipment from anywhere in the world. The Network Bridge joins the company's Industrial Cellular Gateway. Both solutions' remote connections are handled through ProSoft Connect (photo), a secure, cloud-native platform designed to help users realize benefits from the industrial internet of things (IIoT). — *ProSoft Technology, Bakersfield, Calif.*
www.prosoft-technology.com

Wireless adapter enables IIoT for hazardous areas

The new THUM Adapter (photo) has been certified as explosion-proof for in U.S. and Canada. The wireless adapter, designed to operate in hazardous areas, retrieves valuable and formerly stranded data to provide insight for planned maintenance and avoid costly unplanned shutdowns. The device converts a wired HART signal to WirelessHART, and transmits the wireless data to a Gateway. The Gateway connects to the host systems via an industry-standard wired connection, usually Modbus or Ethernet. The diagnostic and process data accessed by the THUM Adapter provides users with insight to their process and helps them plan maintenance to avoid unplanned shutdowns. The THUM Adapter connects directly onto HART devices via threaded conduits, removing the need for a barrier. — *Emerson Automation Solutions, Shakopee, Minn.*
www.emerson.com/wireless-thum

Emerson Automation Solutions

A controller for wastewater-treatment applications

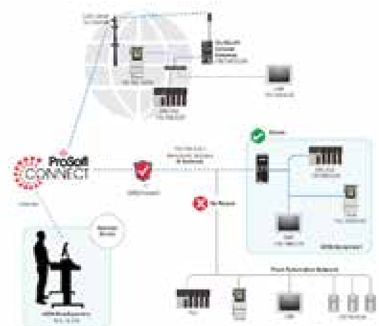
Introduced last year, the W900 Series Controller (photo) enables powerful programming for complete control of chemical metering pumps and valves in a broad range of water-treatment applications. With easy, icon-based programming on the large touchscreen display, the W900 can be configured to control multiple outputs using one of many pre-engineered algorithms. Four I/O slots permit exceptional flexibility to utilize almost any type of sensor, including pH/ORP (oxidation-reduction potential), conductivity, disinfection, fluorescence, temperature, level and flow, to name a few. Internet connectivity lets users maintain control via remote access. — *Walchem, Iwali America Inc., Holliston, Mass.*
www.walchem.com

Walchem

Measure pipeline flowrates with this flow computer and terminal

The Y-Flow product family consists of the Y-Flow YFFC (field flow computer; photo) and Y-Flow YRTU (remote terminal unit). The Y-Flow YFFC is a low-power, orifice-flow computer designed to measure AGA 3 (American Gas Assn.) orifice gas flow and the Y-Flow YRTU is a low-power remote terminal unit designed to measure various complex AGA gas flow calculations, as well as remote control applications. The Y-Flow YFFC utilizes the company's EJX910A multivariable transmitter capsule and communication board. The multivariable capsule and communication board are integrated into the flow computer as a single unit, thus reducing the cost of ownership and providing an accurate and precise measurement. The Y-Flow YRTU allows an external turbine meter, ultrasonic meter, multivariable transmitters and Coriolis meter to be connected to measure complex AGA gas flow calculations. — *Yokogawa Corp. of America, Newnan, Ga.*
www.yokogawa.com

Yokogawa



ProSoft Technology

Wireless operating panel with multi-touch & safety functions

The wireless handheld panel HGW 1033 (photo, p. 22) enables data transfer without long cables in production sites. The mobile panel has

Note: For more information, circle the 3-digit number on p. 62, or use the website designation.

Sigmatek

Mitsubishi Electric Automation

Phoenix Contact USA

ITW Vortec

a 10.1-in. multitouch display (PCT) that is suitable for industrial applications and offers a wide range of visualization options and an intuitive operating concept. As with function-oriented data, safety data are transmitted via the standard WLAN network, but according to the Black Channel Principle. With the wireless HMI (human-machine interface), the machine operator can flexibly select the inspection points and operate multiple machines, robots or system units at the same time with only one panel. For this purpose, a safe seven-segment display for machine identification is integrated. A dual-core EDGE2 Technology processor provides the necessary visualization power. — *Sigmatek GmbH & Co. KG, Lamprechtshausen, Austria*
www.sigmatek-automation.com

This CNC features intuitive touchscreen operation

The M80W computer numerical controller (CNC; photo) is this company's latest addition to its industry-proven M8 Series CNCs. The M80W features a touchscreen Windows-based display that is separate from the control unit, providing expandability and flexibility. Incorporating the latest operating system and slim personal computer, the M80W includes two expansion slots for 32 GB SD cards, allowing OEMs and end users to add up to 64 GB more memory for even greater flexibility. The new M80W CNC was designed for the automotive and machine-tool industries, and is especially useful for applications such as turning centers, machining centers, lathes and mills. — *Mitsubishi Electric Automation, Inc., Vernon Hills, Ill.*
http://us.mitsubishielectric.com

Space-saving surge protection with these thin modules

With modules starting at just 3.5-mm wide, the new Termitrab Complete surge-protective devices (SPDs; photo) can protect up to 572 signals on 1 m of DIN rail. In addition to this ultra-narrow option, the company's newest SPD line includes variants that meet many specific measurement and control needs. The range includes SPDs that use optical monitoring capabilities to troubleshoot and diagnose a system from any location. Local and remote status indication simplifies maintenance. Some modules in the Termitrab Complete line come in a pluggable format. The user can easily remove and replace devices without having to undo or redo connection wiring, saving valuable time. The pluggable versions can be tested using the mobile test laboratory CheckMaster 2. The SPDs are available with Push-in connection technology or screw connection. Eight variants are triple-rated for hazardous locations (IEC Ex, ATEX and Class I, Division 2). A knife-disconnection option makes testing and evaluation more convenient. — *Phoenix Contact USA, Middletown, Pa.*
www.phoenixcontact.com/ttc

Modems now integrated into HART product line

Viator HART modems, previously marketed under Pepperl+Fuchs MACTek Inc., is now a Pepperl+Fuchs branded product. The official integration of the Viator portfolio means that it now has the power of this company's distribution network, making Viator globally available and supported. Bluetooth, RS-232, USB, and USB with PowerXpress Viator models are available, including a Bluetooth model that is designed for use in hazardous locations. HART networks bridge the long distances between the plant and the field, offering cost-effective solutions for data acquisition. Measured values are available on a regular basis, leading to increased quality and more economical operation of process plants. — *Pepperl+Fuchs, Twinsburg, Ohio*
www.pepperl-fuchs.com

Cabinet cooler now certified for hazardous locations

The ProtEX Vortec A/C line of cabinet coolers (photo) has been granted certification for Class I, Division 1, Groups A, B, C and D; Class II, Division 1, Groups F and G; and Class III, after extensive review by Underwriter's Laboratories (UL). The new UL Classification is on top of the existing ATEX Certification for Zones 1 and 21, which complies with the latest EN ISO 80079 36:2016 standard. The unique combination of UL Classification (UL File E356284) and ATEX Certification greatly expands the industries and locations where Vortec enclosure coolers can be

used. The new ProtEX models are small, easily installed and require minimal maintenance costs. In addition, they are certified for ambient temperatures up to 175°F, which is significantly greater than most hazardous-area-rated Freon air conditioners. With dual ATEX and UL certification, these coolers provide an economical alternative to large, heavy air conditioners, which are expensive to purchase and to maintain, says the company. These Vortec models offer 900-, 1,500-, 2,500- or 5,000-Btu/h cooling capacity to suit the differing needs of each enclosure and facility. — *ITW Vortec, Cincinnati, Ohio*
www.vortec.com

This PLC is first to be awarded critical certification

Last August, the ControlEdge programmable logic controller (PLC; photo) received ISASecure Embedded Device Security Assurance (EDSA) Level 2 certification by exida, the ISO 17065 accredited certification body who conducted the assessment. The certification recognizes the integrity of both the PLC and its development lifecycle, and includes rigorous communication robustness testing, as well as functional and software-development security assessments. ControlEdge PLC is said to be the first PLC to be awarded the ISASecure Level 2 certification, which builds on the Level 1 capabilities by providing additional security features, such as the confidentiality and integrity of data at rest and in motion, detection of unauthorized changes and additional protection against Denial of Service attacks. The ISASecure-compliant controller has advanced features, including a secure boot capability to prevent uploading of unauthorized software and a built-in firewall. PLC communication can also be secured using IPSec to prevent man-in-the-middle attacks and unauthorized access. — *Honeywell Process Solutions, Houston*
www.honeywellprocess.com

Honeywell Process Solutions

IDEC

R. Stahl

Siemens AG

A small, yet powerful — and smart — PLC

The MicroSmart FC6A Plus (photo) is a powerful PLC, with up to 2,060 local I/Os. With its expanded I/O capacity, the FC6A Plus can control and monitor the largest machines or entire small-scale manufacturing facilities, a capability seldom found in a micro PLC, says the company. To ensure high-level performance with this expanded I/O count, basic instructions can be executed in the extremely fast speed of 21 ns, and program memory is 800 kB (100 K steps), much larger than other micro PLCs. These capabilities are combined with extensive data memory, more than double the capacity of a typical micro PLC. These features allow the FC6A Plus to handle large programs with complex control requirements, such as PID, flow totalization and recipes. Two models are available, each with 24-V d.c. input power. The 16 I/O model has eight inputs and eight relay or transistor outputs. The 32 I/O model has 16 inputs and 16 transistor outputs. Each model also includes an integral 0–10-V d.c. analog input with 12-bit resolution. Each model can accommodate up to three plug-in discrete, analog, serial communication or Bluetooth cartridges. Each discrete cartridge has four discrete I/O points, either four inputs or four outputs. Each analog cartridge has two analog I/O points, either two inputs or two outputs. Up to 63 I/O expansion modules can be added. This gives the FC6A Plus the capability to handle up to 2,060 I/Os with a maximum of 511 analog I/Os. — *IDEC Corp., Sunnyvale, Calif.*
www.idec.com/usa

Compact Ex-d enclosures for control and terminal boxes

This company's ATEX- and IECEx-certified empty housings (photo), with explosion protection type Ex d, enable highly flexible structuring of terminal and control boxes. The enclosures are suitable for applications in Zone 1, 2, 21 or 22, for both gas- and dust-hazardous environments. Series 8250 includes cost-effective housings with sizes from 250 × 150 × 110 mm up to 540 × 360 × 300 mm. Made of seawater-resistant aluminum, the enclosures are corrosion resistant, reliable and durable. Thanks to their innovative design, these housings weigh almost 15% less than other Ex d enclosures on the market, says the company. They are universally applicable as terminal boxes, as machine- or motor-control units or as distribution boxes. The enclosures can be individually equipped with operating elements and signaling devices. Flameproof cable glands of Ex d type protection are available for direct cable entry into the enclosures. With IP66 degree of protection and a wide temperature range from –60 to 70°C (on request, up to +130°C), the enclosures are suitable for worldwide use in industries such as machine building, offshore applications, chemical, pharmaceutical and others where explosion-protected equipment are mandated to comply with international standards.— *R. Stahl, Waldenburg, Germany*
www.r-stahl.com

An economical IPC for industrial applications

This company is now offering an economical, basic panel PC, Simatic IPC377E (photo). The Simatic IPC377E Basic Panel PC is based on Intel Celeron processor technology and represents a new IPC platform that has been specifically developed to optimize cost for PC-based applications in the industrial and industry-related environments. The Simatic IPC377E combines the openness and performance of an industrial PC with a long-lasting, robust display with anti-glare glass front, analog-resistive with single-touch operation, scratchproof and resistant to chemicals. The display is available in three sizes: 12-, 15- or 19-in. diagonal screen. The Simatic IPC377E Panel PC provides a preconfigured, turnkey solution well suited for all industrial applications, especially for economical implementation of HMI (human-machine interface) applications, the acquisition and networking of production and energy data in production environments, such as assembly workstations, warehouses and logistics systems, or for standard applications in the image-processing field. It is easy to integrate into existing machines and plant concepts. — *Siemens AG, Munich, Germany*
www.siemens.com ■

Gerald Ondrey

Throttling valves provide dependable shutoff

Clampseal throttling valves (photo) are well suited for severe-service applications that require repeatable flow control and shutoff. The valves are available in 0.5- through 4-in. sizes with a variety of standard forging materials. The valves' venturi is an integral part of the removable seat. Both the seat and the stem assembly are easily changed inline in the event of a flow characteristic change or excessive corrosion or erosion. The orifice is sized to keep fluid velocity across the seat below damaging levels. The exit orifice angle is designed to minimize downstream piping erosion and noise. The pressure-seal bonnet provides service access with no need to cut welds or replace seal rings or gaskets. — *Conval, Somers, Conn.*
www.conval.com

These blenders now feature added operator safety

This company now offers protective light curtains for its tumble blenders (photo) to provide automatic safety shutoff whenever an operator crosses a defined security boundary. Due to the nature of the rotating mix chamber, a safety railing is supplied as standard on these blenders, and the addition of optional light curtains further improves operator safety. The blenders are also equipped with an explosion-proof brake motor, a 50-psig heating and cooling jacket and a NEMA-rated control panel with a purge system suited for Class 1, Div. 1 hazardous locations. Standard blender models are rated for bulk densities up to 125 lb/ft^3, and specialty designs are available for higher densities. These blenders are designed for batch operations that require the dispersion of extremely small components and low-shear intensity. — *Charles Ross & Son Co., Hauppauge, N.Y.*
www.mixers.com

Analyze emissions for regulatory and maintenance purposes

The new E8500 PLUS emissions analyzer (photo) is a portable tool for emissions monitoring and testing designed for regulatory and maintenance use in boilers, burners, engines, turbines, furnaces and other combustion applications. Features new to this model include NO and NO_2 sensors for True NOx measurements, a new display screen and keypad design, easier filter replacement and inspection and an expanded internal memory with capacity for up to 2,000 tests. The E8500 PLUS is also equipped with a new sample-conditioning system for low NOx and SO_2 scenarios. The analyzer has electrochemical sensors for O_2, CO, NO, NO_2, SO_2 and H_2S and now also has an option for sensing volatile organic compounds (VOCs). — *E Instruments International, Langhorne, Pa.*
www.e-inst.com

New check valves are compliant with NACE specifications

This company's Zero Leak Check line of check valves (photo) now includes new valve configurations that are manufactured entirely from materials that are compliant with the National Association of Corrosion Engineers (NACE) specification MR0175/ISO 15156. They also feature custom polymeric valve seats that ensure no leakage of fluids at pressures up to 15,000 psi (differential) and at temperatures up to 400ºF. The valves are also self-retained without the need for O-rings, facilitated by the use of a locking end that securely locks the valves in place and prevents any bypass leakage. Available with diameters from 0.187 to 0.500 in. (4.75 to 12.7 mm), configurations may also include integrated safety screens or restrictors for added protection and performance. These NACE-compliant valves are useful in applications that require zero leakage at high differential pressures in high-temperature, corrosive environments. — *Lee Products Ltd., Gerrards Cross, U.K.*
www.leeproducts.co.uk

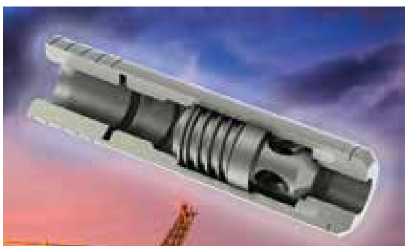
A 'one-size-fits-all' frame makes this pump simple to maintain

The model 1400 horizontal-end suction pump (photo, p. 26) features a heavy-duty cast-iron frame design that incorporates integrally cast support and ribbed mounting feet, and fits all pump sizes. The frame has a

Conval

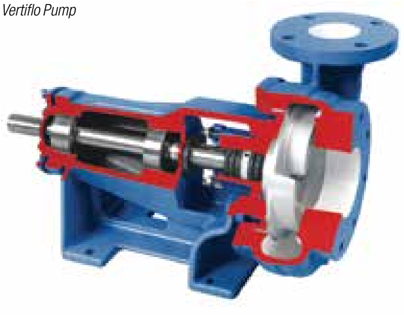
Charles Ross & Son

E Instruments International



Lee Products

Vertiflo Pump



Scaletron Industries

Alfa Laval

Transducers Direct

back pull-out design feature that allows for easy inspection, service and maintenance without disturbing the piping to the pump. The pump has external impeller adjustment, and the semi-open impeller design accommodates passage of solids or fines. All impellers have balance holes near the hub, which reduce thrust load and pressure in the packing or seal area. Wiping vanes reduce axial loading and prevent dirt from entering the sealing area. Packing or various mechanical seal arrangements are available as standard options. Requirements for pumping clear and corrosive liquids can be satisfied with capacities up to 3,600 gal/min, heads up to 275 ft and temperatures as high as 250°F. — *Vertiflo Pump Co., Cincinnati, Ohio*
www.vertiflopump.com

A volumetric screw feeder for confined workspaces

The new Model VMF-90A volumetric screw feeder (photo) is designed for automated additive dosing in water treatment and chemical processes. This new model is simplified compared to previous models and offers more flexibility for installation in confined workspaces. Integrating the VMF-90A into existing feeder systems typically requires little or no redesigning, even where there is limited installation space, says the company. For feeding dry powdered or pelletized materials, the VMF-90A feeder achieves feedrates of up to 10.19 ft^3/h. The unit uses gravimetric feeding enhanced with a built-in mechanical cam-actuated hopper agitator. The agitator continually conditions the material being added to promote uniform flow, a feature that is particularly useful when working with materials that tend to clump. Also available is an optional "loss-in-weight" weighing system for applications where enhanced precision is required. This option comprises an integrated precision scale with four load cells and a digital scale controller. — *Scaletron Industries Ltd., Plumsteadville, Pa.*
www.scaletronscales.com

High-alloyed valves are designed for use with aggressive liquids

The UltraPure model (photo) from the Unique Mixproof valve product line is designed to meet the standards of biotechnology and pharmaceutical applications. Valves are packaged to ensure full traceability and are available in high-alloy materials, such as Hastelloy C22 and AL6XN. These alloys help to meet demands for corrosion resistance against aggressive media, including buffer solutions, cleaning liquids, high-salt solutions and more. Unique Mixproof valves are also suitable for use with hygienic products that contain high chloride concentrations or low pH levels. — *Alfa Laval AB, Lund, Sweden*
www.alfalaval.com

A cybersecurity platform for multi-vendor automation systems

This company's Cyber Integrity 6.0 platform now includes continuous vulnerability management, providing immediate, comprehensive visibility into vulnerability risk within industrial process control networks. Cyber Integrity works across the multi-vendor automation environment, providing foundational cybersecurity, enterprise scalability and platform independence. It also automates internal and regulatory compliance reporting. The system enables users to gather and maintain an inventory of traditional and proprietary operational technology assets, determine baselines and monitor for unauthorized changes to cyber configurations and implement programs for system backup and recovery. Users can also automate an enterprise-wide continuous vulnerability- and patch-management process — *PAS Global, LLC, Houston*
www.pas.com

Monitor pressure and temperature in refrigerant lines

The new TDWLB-LC series wireless transducer (photo) is designed for use with sensors installed on refrigerant lines to monitor both pressure and temperature, and ensure that the proper amount of refrigerant is in the system and it is running efficiently. Users can configure sensor nomenclature and set high or low alarms in a free mobile app, as well as view subcooling and superheating calculations. Data can be viewed remotely with a wireless gateway companion product.

The device is very lightweight, due to its composite material of construction. The TDWLB-LC transducer offers resolution and noise immunity, while using very little power, says the company. — *Transducers Direct, Cincinnati, Ohio*
www.transducersdirect.com

Use this peristaltic pump in disinfection applications

The new Qdos 20 peristaltic pump (photo) was developed for metering sodium hypochlorite in disinfection applications with flowrates up to 20 L/h at a maximum pressure of 7 bars. The Qdos 20 peristaltic pump technology uses two tube channels where the channels are operated out of phase. The Qdos 20 reduces pulsations via alternate tube compressions, ensuring pulsation is balanced out. This results in almost continual positive fluid displacement and consistent metering of chemicals into the process. The contained pumphead design features integral leak detection, reducing waste and eliminating operator exposure to chemicals. The pump's user interface provides control via manual, 4–20-mA, contact or Profibus control. — *Watson-Marlow Fluid Technology Group (WMFTG), Cornwall, U.K.*
www.wmftg.com

These tube fittings drastically increase working pressures

The Gyrolok XP system of tube fittings (photo) is specifically designed to address the challenges of assembling fittings onto a wide range of corrosion-resistant, heavy-wall small-bore tubes. These fittings can grip heavier wall tubes, which is said to increase working pressures by up to 80% over conventional tube fittings, allowing XP fittings to be used on tubing with higher pressure ranges, including exotic alloy tubing used in severe-service applications. Simplified installation helps to ensure that fittings cannot be overtightened. The fittings have been validated in sys-

Watson-Marlow Fluid Technology Group (WMFTG)

HOKE

Adaptive Wireless Solutions

Emerson

Yokogawa

tems using a variety of austenitic and high-performance alloys, over a wide range of tubing sizes and thicknesses. Key applications for these fittings include process instrumentation, sour-gas and other high-corrosion processes, chemical injection, sampling systems and hydrogen processing. — *HOKE, a division of Circor Instrumentation, Spartanburg, S.C.*
www.hoke.com

Wireless instruments that never need new batteries

This company has developed WirelessHART instrumentation devices (photo) with batteries that are expected to last the entire life of the device. The batteries are engineered to minimize energy usage based on an in-depth microsecond-by-microsecond analysis of a unit's power consumption. This avoids the requirement that maintenance personnel conduct battery-replacement tasks, which can be especially burdensome in remote or hazardous areas. Battery-replacement tasks also prove to be time-consuming over the lifetime of an asset, especially in plants that have hundreds or thousands of WirelessHART instruments. Longer-lasting batteries also eliminate the risk of shutdown if dead batteries are not proactively replaced. The instruments equipped with these new batteries include devices that provide critical information on temperature, pressure, flow and humidity. — *Adaptive Wireless Solutions, Hudson, Mass.*
www.adaptive-wireless.com

Enhance plant safety with new SIL-certified flowmeters

Facilities with safety instrumented systems can now take advantage of the new SIL (safety integrity level) 2/3 functional safety certification of the Rosemount 8800 Vortex flowmeters (photo), per IEC 61508, which can help mitigate risk, enhance plant safety and protect personnel. The non-clog Rosemount 8800 Vortex portfolio offers safety and reliability features, such as online removable sensors to reduce process downtime and a critical process valve for aggressive applications, which increases personnel safety by preventing exposure to hazardous fluids. A variety of configurations are available to suit a many different requirements, including flanged, wafer, reducer, dual and quad meter body styles, supporting installations in lines up to 12-in. in diameter. Per an accredited third-party assessment, a single Rosemount 8800 Vortex meter may be used in processes requiring up to SIL 2 protection. The Dual Vortex meter is capable of up to SIL 3 and offers a simple drop-in solution to reduce installation costs. — *Emerson, St. Louis, Mo.*
www.emerson.com/vortex

Pressure gages with enhanced protection against vibration

This company's 1008S small-footprint pressure gages are available in diameters of 40 or 50 mm. A NEMA 4/IP66 water-ingress rating and a stainless-steel case allow the 1008S to be used outdoors or in harsh environments where corrosion resistance is required. Liquid fill, or the company's patented Flutter Guard movement-enhancement option, protect the gage and make it easier to read in high-vibration installations. Reading errors are reduced due to the presence of a "zero box" instead of conventional dial pins, which ensures integrity and system control. The 1008S model is available in ranges up to 20,000 psi. — *Ashcroft Inc., Stratford, Conn.*
www.ashcroft.com

A new release of this pipeline-management application

This company has released Enterprise Pipeline Management Solution (EPMS) R1.03, the latest version of its enterprise-level pipeline applications suite (photo). Developed for deployment in the pipeline operations management environment, EPMS supplements a core SCADA platform with specific gas and liquid applications that enable a pipeline operator to manage delivery contracts and associated logistics in a safe, cost effective and efficient manner. Among the new functionality is enhanced interface management. When transitioning from one product to another in a pipeline, a trans-mix that is of a certain volume and that varies in quality will be formed at the interface between the adjacent fluids. With EPMS R1.03, multiple product cuts from the

same interface can be performed, for the easy management of quality gradations. Furthermore, the use of product density meters to detect variations in interface quality based on color and sulfur content is now supported. The new release also offers enhanced batch management. For greater flexibility, continuity and energy efficiency, EPMS R1.03 supports side-stream injection and stripping as a product batch passes an intermediate delivery or receiving site. — *Yokogawa Corp., Tokyo, Japan*
www.yokogawa.com

Intelligent blower controller delivers energy efficiency

The Sigma Air Manager (SAM) 4.0 (photo) is a core control component of a blower station and enables users to take advantage of Industry 4.0 services. It acts as the central controller and controls individual machines with maximum efficiency while precisely adjusting the flow capacity to match flowrate demand. The only required input from the process control system is the desired differential pressure value — the SAM 4.0 then ensures optimal control of all blowers. Partial-load bridging and individual solutions are therefore obsolete, along with complicated setups. Now, all applications are supplied by one central blower station with a master controller that analyses operating data in seconds and simulates various scenarios in order to select the most efficient solution. — *Kaeser Kompressoren SE, Coburg, Germany*
www.kaeser.com

This new bimetal temperature switch has UL approval

The new model TFS135 bimetal temperature switch (photo) has been designed for a wide range of applications. It is suitable for switching voltages of up to 250 V a.c. (2.5 A) and has a UL approval (cURus) for the North American market. The TFS135 conforms to the E.U. low-voltage directive. It has been designed for switching temperatures of 50–130°C, selectable in stages of 5K and set permanently on delivery. With a vibration resistance of up to 10 g, the TFS135 operates reliably even under harsh conditions. The new switch model is primarily used for the protection of plants and end devices against overheating. — *WIKA Alexander Wiegand SE & Co. KG, Klingenberg, Germany*
www.wika.de

Durable LED light fittings with universal mounting options

These LED pendant light fittings (photo) have various installation options for worldwide use in Zones 2, 21 and 22. The new 6470 pendant light fittings are suitable for general lighting in chemical, oil-and-gas and other industries, due to the efficient lighting and mounting options. Different cover variants enable installation as ceiling, wall, pole or pendant light fitting for uniform illumination of production halls, storage facilities or pathways. The lights have a high optical efficiency and provide a luminous flux of 8,000 lumens, with a power consumption of 65 W. The luminous intensity distribution of the low-glare light fittings can be varied by means of different reflectors. These are powder-coated enclosures made of saltwater-resistant aluminum and the lens consists of toughened glass. — *R. Stahl, Waldenburg, Germany*
www.r-stahl.com

Silicone hose assemblies for hygienic applications

The new ElaSil range of silicone hoses (photo) is suitable for high-media-purity requirements and is easy to clean. Typical applications include ultrafiltration, fermentation, ultrapure water production, WFI (water for injection) and use as a transfer hose. ElaSil conforms to FDA and USP Class VI and meets the 3-A Sanitary Standard. The homogeneous hose construction consists of a smooth lining and cover of platinum-cured, translucent, phthalate-free silicone and exhibits a combination of high flexibility and kink resistance throughout the temperature range from –60 to 200°C. Hose sizes of DN 13 to 102 mm are available, along with a large range of commonly used hose fittings. — *Elaflex-Gummi Ehlers GmbH, Hamburg, Germany*
www.elaflex.de/elasil ■

Mary Page Bailey and Gerald Ondrey

Kaeser Kompressoren

WIKA Alexander Wiegand

R. Stahl

Elaflex-Gummi Ehlers

Industrial Combustion Products

Department Editor: Scott Jenkins

All chemical process industries (CPI) operations involving combustion need to be concerned with the emission of combustion products, due to their potential environmental and health impacts. This one-page reference provides information about several of the most common combustion byproducts from industrial heating processes.

Combustion provides heat for many industrial processes and accounts for over 80% of the power used by turbines to generate electricity. The listing in the box shows several operations within the CPI where combustion is used. Modern industrial combustion — both for process heat and power generation — is characterized by an increasingly diverse fuel supply and a greater need to reduce potentially polluting emissions.

Combustion products

The following sections discuss some of the main potential pollutants that result from the combustion of fossil fuels in an industrial setting.

Carbon dioxide. CO_2 is the principal product from the combustion of fossil fuels. It is a colorless, odorless gas with a density greater than air. For each pound of carbon burned in a CPI process, 3.67 lb of CO_2 is released. CO_2 is a greenhouse gas, and is present in the earth's atmosphere at concentrations around 400 parts per million (ppm). Its IDLH (immediately dangerous to life and health) concentration is 40,000 ppm

Carbon monoxide. CO is a colorless, odorless gas that is formed when carbon in fuel is not burned completely. Adverse health effects can occur at CO concentrations as low as 10 ppm with prolonged exposure. In the atmosphere, CO can be a component of smog.

Oxides of nitrogen (NO_x). Oxides of nitrogen (primarily NO and NO_2) form when fuel is burned at high temperatures. The primary sources of NO_x include motor vehicles, power generation facilities and other industrial sites, as well as commercial and residential sources. The U.S. Environmental Protection Agency (EPA) requires control of NO_x in combustion, because NO_x reacts with organic vapors in the presence of sunlight to produce ground-level ozone. The low-cost way to limit NO_x is to do so upstream in the combustion process, for instance, via low-NO_x burners, and low-oxygen firing systems.

In a flame, NO_x can be formed by three different processes to generate thermal NO_x, fuel NO_x and prompt NO_x. Thermal NOx is produced at high temperatures by elementary reactions of the Zeldovich mechanism. Fuel NO_x is produced from combustion of nitrogen-containing fuel components. Fuel-generated NO_x can be avoided by using fuels without significant quantities of nitrogen-containing compounds.

Prompt NO_x is produced by radical reactions in the flame. In most combustion systems, thermal NO_x is the dominant production channel, and NO_x emissions can be controlled by limiting the flame temperature.

Sulfur byproducts. Sulfur dioxide (SO_2), belongs to the family of sulfur oxide gases (SO_x). These gases dissolve easily in water. Sulfur is prevalent in all raw materials, including crude oil, coal, and ores that contain common metals, such as aluminum, copper, zinc, lead and iron.

SO_x gases are formed when fuel containing sulfur, such as coal and oil, is burned, and when gasoline is extracted from oil, or metals are extracted from ore. SO_2 dissolves in water vapor to form acid and interacts with other gases and particles in the air to form sulfates and other products that can be harmful to humans and the environment.

Particulate matter. Particulate matter (PM) is the general term used to describe a mixture of solid particles and liquid droplets found in the air. PM can either be emitted directly or formed in the atmosphere. Different sources of particles include:

- "Primary" particles are formed from combustion sources and are emitted directly into the atmosphere. Examples of primary particles are dust from roads or black carbon (soot).
- "Secondary" particles are formed in the atmosphere from primary gaseous emissions. Examples of secondary particles are sulfates formed from SO_2 emissions from power plants and industrial facilities; nitrates formed from NO_x emissions from power plants, automobiles, and other combustion sources; and carbon formed from organic gas emissions from vehicles and industrial facilities.

Some particles are large enough to be seen as dust or dirt. Others are so small they can be detected only with an electron microscope.

- $PM_{2.5}$ describes the "fine" particles that are less than or equal to 2.5 μm in diameter
- "Coarse fraction" particles are greater than 2.5 μm, but less than or equal to 10 μm in diameter
- PM_{10} refers to all particles less than or equal to 10 μm in diameter (about one-seventh the diameter of a human hair) ■

MAJOR PROCESSES INVOLVING COMBUSTION

Combustion heating temperatures range from 400–500K for bread baking and paint drying, to 2,000K for cement and steel making.

- Metal melting
- Metal heat treating
- Curing and forming
- Drying
- Calcining
- Clay firing
- Agglomeration
- Glass melting
- Fluid heating
- Distillation
- Food production
- Ore roasting

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Isopropanol Production from Propylene

By Intratec Solutions

Isopropanol (isopropyl alcohol) is among the most commonly produced lower alcohols — ranked third in commercial production behind methanol and ethanol. Isopropyl alcohol is used as a chemical intermediate for compounds such as methyl isobutyl carbinol, methyl isobutyl ketone and isopropyl acetate, as well as in personal care and household products, pharmaceuticals, coatings and ink solvents, and as a processing solvent, among other uses.

The process

The following paragraphs describe a typical indirect propylene-hydration process for the production of isopropanol. In this process, refinery-grade (RG) propylene reacts with sulfuric acid to form isopropyl alcohol sulfates, which are then reacted with water to form isopropanol (Figure 1).

Reaction. RG propylene gas is fed to the absorber reactor, where it is absorbed by sulfuric acid, forming isopropyl hydrogen sulfate and di-isopropyl sulfate. The liquid stream containing the sulfates formed in the first step is fed to the stripper reactor. Steam is fed to the stripper to hydrolyze the sulfates and generate isopropanol, which is flashed as the vapor product. This gaseous stream is scrubbed with a caustic solution to neutralize any residual acid. This results in a liquid stream of crude isopropanol that is routed to the isopropanol purification section. Any uncondensed vapors are compressed and recycled to the absorber reactor. The stripper liquid effluent, comprising dilute sulfuric acid, is reconcentrated and recycled to the absorber reactor.

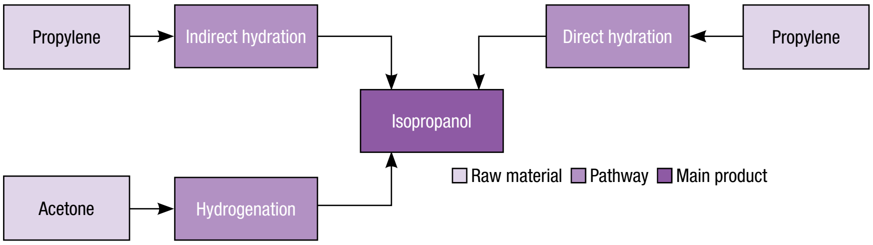

FIGURE 2. There are several possible production routes to isopropanol

Propylene recovery. The absorber off-gas, containing unreacted propylene, propane and byproduct vapors, is scrubbed with a caustic solution to neutralize any entrained sulfuric acid and recover sulfates or ether, which may also be entrained in the vapor. The off-gas from the scrubber is sent to the propylene column, where propylene raw material is separated from propane and recycled to the absorber reactor.

Purification. The crude isopropanol from both the caustic scrubber and the stripper reactor are directed to an ether separation step, where di-isopropyl ether (generated in side reactions) is separated and recycled to the absorber reactor to react with sulfuric acid, forming sulfate and isopropanol. The ether-free crude isopropanol is transferred to the alcohol column for removal of high-boiling impurities. The overheads product from the alcohol column comprises an azeotropic mixture of isopropanol and water. Finally, dry isopropanol is produced after dehydration by means of azeotropic distillation using di-isopropyl ether as an azeotroping agent.

Production pathways

The main raw materials for isopropanol manufacture are propylene and acetone (Figure 2). Propylene is reacted with water directly, or indirectly (process described above), to form isopropanol. Acetone, in turn, passes through a hydrogenation process.

Economic performance

The total operating cost (raw materials, utilities, fixed costs and depreciation costs) estimated to produce isopropanol was about $1,480 per ton of isopropanol in the first quarter of 2014. The analysis was based on a plant constructed in the U.S. with capacity to produce 200,000 metric tons per year of isopropanol.

This column is based on "Isopropyl Alcohol Production from RG Propylene – Cost Analysis," a report published by Intratec. It can be found at: www.intratec.us/analysis/isopropyl-alcohol-production-cost. ■

Edited by Scott Jenkins

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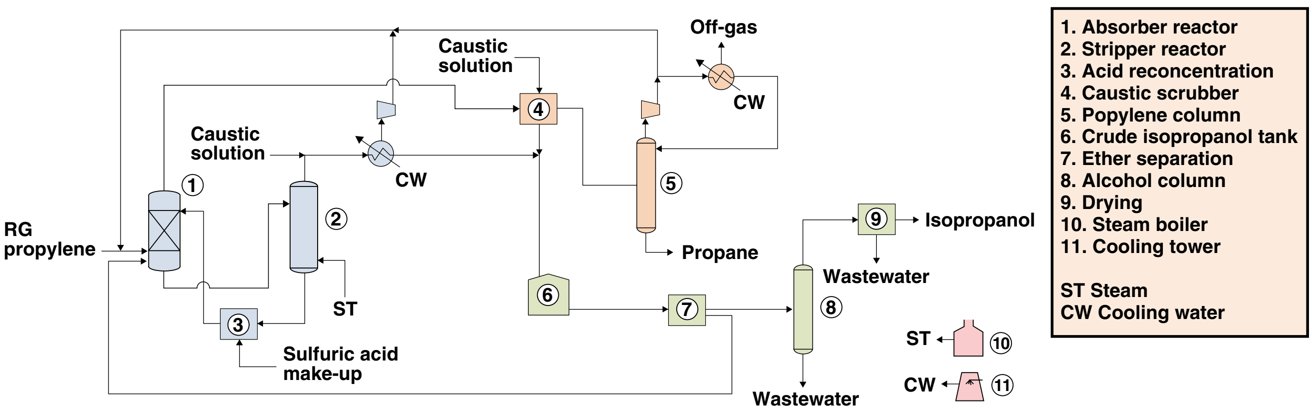

FIGURE 1. The diagram shows the production of isopropanol from refinery-grade propylene via indirect hydration

Part 1

Rotating Machines: Digital Technologies to Enable Predictive Maintenance

Predictive maintenance for rotating machinery is gaining prominence as plant operators embrace analytics and learn how to approach their operating benchmarks

Diego Pareschi
ABB

IN BRIEF

THE MOVE TO PREDICTVE

FAILURES LEAD TO DOWNTIME

REMOTE MONITORING

DATA ANALYTICS ADDS POWER

ORGANIZED KPI DATA GET RESULTS

Rotating machines, such as motors, compressors, pumps and turbines, are critically important components of plant operations, and must perform reliably and efficiently at all times. However, given the high pressures and harsh environments in which these machines operate, equipment failures are all too common.

FIGURE 1. Advances in digitalization and connectivity have helped usher in more proactive maintenance practices

To keep equipment running for as long as possible, companies must invest in maintenance. Historically, many aspects of these maintenance tasks were less than ideal, but few alternatives existed. In many cases, simple visual inspection was used to determine equipment condition. Often, plant managers ran equipment until failure instead of performing preventive maintenance. This reactive maintenance approach results in unscheduled downtime, higher labor costs and faster deterioration of assets.

In order to avoid these costly scenarios, many companies began to embrace preventive maintenance. With preventive maintenance strategies, statistical trend data and analysis are used to determine the optimal intervals for servicing equipment. The biggest challenge with this approach is that it is time-based. Equipment is inspected and addressed at regular intervals regardless

FIGURE 2. There are many important factors to consider when configuring wired and wireless instruments on different types of rotating machinery

FIGURE 3. Handheld devices, which enable more effective remote-monitoring programs, are becoming more widely used in the CPI

of a truly identified need to do so. It is thus possible to induce failure by tampering with equipment more often than necessary. In some cases, equipment is replaced without assessing its remaining life or current performance. Some of these challenges are being addressed through advanced digital technologies that can better predict and diagnose anomalous equipment behavior (Figure 1). Table 1 summarizes the evolution of maintenance practices typically used in the chemical process industries (CPI). This article examines the benefits of predictive maintenance strategies for rotating machinery and also provides guidance in configuring data-analytics platforms and organizing operational benchmarks for rotating machinery.

The move to predictive

With vast computational power and the advent of low-cost sensors, preventive maintenance is transitioning into predictive maintenance. Predictive, or condition-based maintenance, as it is also called, identifies issues in equipment before they present serious risks to plant operations or personnel. In a predictive maintenance approach, plant managers use evidence-of-fault to determine how to maintain equipment or even when to replace it. Accurate information on equipment condition enables companies to minimize failure risks, reduce maintenance costs and maximize asset availability.

Critical equipment that can cause a shutdown or other loss of production in the event of a failure are typically outfitted with instrumentation, such as continuous vibration probes, accelerometers, displacement transducers, phase detectors and speed detectors (Figure 2). They also are outfitted with pressure and temperature transducers that measure conditions that change more slowly, such as bearing temperature or oil pressure.

Because bearings are extremely critical components of rotating machines, sensors are frequently installed directly on the bearing to measure vibration and bearing surface temperature. Other sensors are installed on the machine housing to capture overall vibrations, and in the case of electrical motors, to measure critical electrical parameters, such as voltages and currents.

Wired instrumentation also is used in less critical equipment, but this is uneconomical, so monitoring is often limited to high- and medium-criticality machines. Wired

TABLE 1. STANDARD MAINTENANCE STRATEGIES

Maintenance strategy	Maintenance approach	Possible result
Reactive	Fix equipment when broken	High cost, lost production
Preventive	Schedule maintenance on a time basis	Effective resource scheduling, but possible failure inducement by regularly touching equipment whether it needs it or not
Predictive	Condition-based monitoring	Maintenance based on equipment state

TABLE 2. CONSEQUENCES OF FAILING ROTATING MACHINES [*1*]

Sub-system	Actual failure rate per year	Failure (f) rate ranges	Actual downtime hours per failure	Failure consequences downtime hour ranges	Total risk
Compressor, combustion chamber, turbine	0.22	1–0.1 f/yr	24	10–100	Serious
Fire protection	0.24	1–0.1 f/yr	1	0–10	Medium
Generator	0.72	1–0.1 f/yr	45	10–100	Serious
Lube oil	0.25	1–0.1 f/yr	13	10–100	Serious
Fuel gas	0.25	1–0.1 f/yr	30	10–100	Serious
Load gear	0.20	1–0.1 f/yr	2	0–10	Medium
Vibration monitor	0.20	1–0.1 f/yr	117	100–1,000	High
Control system	0.68	1–0.1 f/yr	40	10–100	Serious

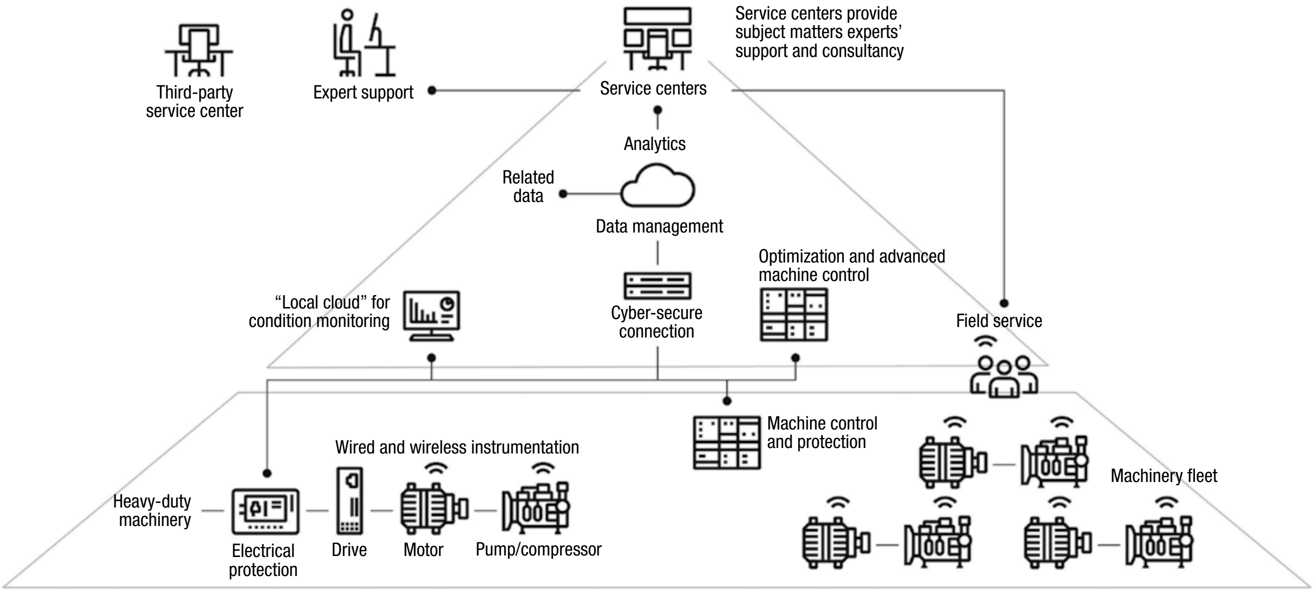

FIGURE 4. An effective predictive maintenance strategy includes connectivity between many operational levels and devices

sensors allow for continuous machine monitoring, while wireless sensors measure machine status periodically (for instance, once per hour). Wired instruments are better for protecting the machine, while wireless sensors are good for monitoring overall machine condition. Moreover, wired sensors can capture some types of signals and information not achievable wirelessly.

However, unlike in years past, the cost of wireless sensors is decreasing significantly, and they are also becoming easier to install, so they now provide a suitable solution for low-criticality equipment. The most common sensors measure vibrations (accelerometers), surface temperatures and magnetic fields. Prior to wireless technologies, the only way to obtain those signals was to install dedicated probes on the electrical feeding lines, but this is expensive, and therefore, uncommon for low-criticality machines.

Failures lead to downtime

Rotating machines usually operate from 1 to 10,000 rpm and withstand high pressures and temperatures. These factors, combined with centrifugal and centripetal forces, increase wear that will inevitably lead to failure. This could mean several days or weeks of lost production and millions of dollars in downtime and repair costs. To illustrate this point, a risk-assessment study for a gas turbine (Table 2) shows that turbine sub-system failure presents serious risk of significant downtime [*1*]. A 22% failure rate of the compressor, combustion chamber and turbine sub-systems caused an average downtime of 24 hours per failure.

But each individual failure could cause 10 to 100 hours of downtime, leading to significant production losses.

Remote monitoring

The most common technologies used in predictive maintenance of rotating machines are infrared thermography, ultrasound analysis, motor-current signature analysis, oil analysis, partial discharge and vibration analysis. All of these methods use evidence-of-fault to determine the maintenance requirements. Table 3 provides details of these technologies.

Although predictive maintenance provides information for timing maintenance activities accurately, it has limitations. Acquiring data using a handheld device (a common practice) is labor-intensive and takes people away from other more productive activities. It is also difficult to gather data from equipment that is in hard-to-reach areas, or areas that pose a danger to the person collecting the data.

However, advances in wireless technology (including a significant drop in deployment costs) and secure wireless communications allow engineers to monitor equipment remotely (Figure 3). Data can be automatically collected even from the most inaccessible sites, and remotely monitored from anywhere in the world.

This represents a great cost-reduction opportunity, as personnel no longer need to spend valuable time physically visiting and interfacing with every asset to gather data. It also has a positive impact on safety, since remote monitoring allows personnel to avoid dangerous areas of the plant.

Data analytics adds power

While remote monitoring is an exciting advancement, robust data collection and analytics make predictive maintenance truly powerful. Data analytics enables the accurate modeling of conditions and factors that lead to equipment failure, thus allowing plant engineers to stay ahead of problems before they happen. The following is a hierarchy for remote monitoring and data analytics that is currently being used in some CPI plants:

- Field level: Sensors that collect basic data, such as current, temperature and torque, on equipment and send it to an onsite edge device. An edge device, such as a router or multiplexer, serves as an entry portal into core networks
- Edge device: Data streams from sen-

TABLE 3. PREDICTIVE MAINTENANCE METHODS FOR ROTATING MACHINES [2]

Method	Description
Infrared thermography	Uses an infrared camera to detect high temperatures that could indicate imminent equipment failure or premature degradation
Ultrasound analysis	As bearings fatigue, they deform. These irregular surfaces cause ultrasonic sound waves to increase in amplitude
Motor-current signature analysis (MCSA)	Analyzes a three-phase induction motor current to detect faults without taking the motor offline
Oil analysis	Detects anomalies in the machine lubricant through physical testing, particle analysis and spectral analysis
Partial discharge (PD) monitoring	Detects insulation breakdown in the cables, transformers, switchgears and windings of large motors
Vibration analysis	Determines the condition of a mechanical system under various operating conditions by evaluating mechanical vibration. A change in vibration amplitude at specific frequencies can indicate a change in condition

TABLE 4. KPIs FOR CENTRIFUGAL AND AXIAL GAS COMPRESSORS

KPI	Description
Deviation Monitors when compressor measurements have deviated from factory set values	**Deviation from expected head** A reduction in the delivered pressure (or head) has a negative impact on the energy consumption of the compressor and can lead to mechanical stress and damage to the machine
	Deviation from expected flow A reduction in the delivered flowrate has a negative impact on the energy consumption of the compressor that can lead to unexpected surge events that can severely damage the compressor
Fouling Monitors the accumulation of unwanted material on solid surfaces, which can affect equipment function	**Fouling** Systems and methods for measuring fouling in a gas-turbine compressor include a conductivity resistance sensor disposed in a compressor inlet mouth. The degree of compressor fouling is correlated to changes in resistance measured by the conductivity resistance sensor. Measurements of resistance changes are converted into indicators of fouling and used to trigger cleaning of the compressor
Surge limit Monitors if the compressor is working too close to the surge limit in a way that causes undesired activation of the anti-surge control system or excessive gas recycle	**Surge** Surge occurs when the peak head capability of a compressor is reached and flow is reduced. When a compressor approaches its surge limit, some of its components (for example, diffusers and impellers) may start to operate in stall mode
Anti-surge valve performance Monitors if the anti-surge control valve is working properly	**Stiction** Analyzes the response time of the valve to evaluate if the valve would be able to protect the compressor from a fast-surge event. In the case of stiction detection, maintenance on the valve is required
	Leakage detection Detects undesired leakages that can cause a significant increase in the power consumption of the compressor
	Excessive valve travel Evaluates if the valve is poorly controlled, leading to excessive mechanical stress, which could lead to sudden damage to the valve itself, which would make the compressor disable protection against a fast-surge event
	Inadequate valve sizing Detects if an anti-surge valve is incorrectly sized. An incorrect size can cause a significant increase in the power consumption of the compressor (if too large) or poor protection of the compressor in the case of a surge event (if too small)
Compressor control operation Monitors that the compressor controllers (anti-surge, performance control and load-sharing control) are working properly and can ensure the protection level for which they were designed	**Oscillating controllers** Detects when the controllers are interfering with each other, causing excessive oscillations to the process and the machine itself
	Tuning problems Detects when the controllers are tuned inadequately, leading to slow or too fast response. Can lead to poor response to setpoint changes

sors are aggregated and analyzed by sophisticated software algorithms to identify, categorize and prioritize issues. Plant-wide solutions for condition monitoring are implemented, leading to realtime optimization insights

- Cloud: Data from different sites are aggregated into remote service centers and used by subject matter experts to provide advanced services across sites. This allows for collaboration between sites, headquarters and suppliers, leading to better-informed decision-making. Information is also used to support field services

While deploying remote monitoring is challenging, figuring out what to do with all the data is even more challenging. Suppliers are inundating producers with remotely monitored data, but it can be difficult to extract useful and directive information and present it as easy-to-understand data analytics for appropriate actions. A robust data-analytics platform is necessary to provide users with the insights to resolve issues before they become problems and must be part of a larger network of devices and services (Figure 4). The following questions are among those that will be addressed by a well-designed data-analytics platform:

- What are the key performance indicators (KPIs) that should be monitored for rotating machines?
- How should they be categorized and displayed so that users can quickly turn raw information into actions?
- Which KPIs have the highest impact on equipment and, therefore, process performance?
- How are benchmarks used to calculate ideal performance levels?
- How should deviation from ideal performance be analyzed so that mitigating actions can be implemented?
- What kind of notifications should be sent to alert users when there is a problem?

These same technologies can be applied beyond rotating machinery to other equipment types. For non-critical assets, predictive analytics capabilities are more often used to re-think maintenance intervals; for example, how often to perform certain maintenance activities based on actual machine usage instead of time-based intervals. Due to the large volume of equipment in a typical CPI plant, these seemingly small changes can prove to be quite valuable. Multiplied over thousands of assets, those savings in maintenance costs quickly become significant. Even more significant is avoiding production downtime. Keeping production running, incremental margins increasing and orders filled are crucial.

Organized KPI data get results

Data-analytics platforms must automatically identify, categorize and prioritize KPIs so that the most important issues by severity and criticality

are addressed first by operational decision-makers. Table 4 provides some examples of specific KPIs for rotating equipment.

The goal is to give operators an unambiguous view of which issues require immediate attention, which can be monitored, and which are less important but may require attention at a later time. This way, in a few quick views, operators can see critical issues and make important decisions on how to address them. In this scenario, KPIs are categorized into four groups:

- Process: Information regarding the thermodynamic performance of the process machine
- Mechanical: Information regarding the mechanical condition of rotating equipment
- Electrical: Information regarding the condition of electrical equipment, including auxiliary systems, such as switchgears and transformers
- Control: Information regarding performance of the machine control system, including instrumentation and actuators

What operators should get from these systems is a time-series analysis that shows spikes (such as anti-surge control change between 2:30 and 3:00 pm), indicating high deviation from optimal control limits. This information prompts the operator to look more closely to determine the root cause of the deviation and take necessary action.

Data-analytics systems also should alert plant operations via email or text when KPIs exceed set limits, helping them stay informed of issues even when they are away from the site. This promotes faster resolution of problems, improved equipment condition and higher process performance.

Depending on the type of KPI-triggered alert, several actions can be taken:

- If the KPI can trigger a mechanical or electrical service, such as a repair call, then the maintenance engineer issues a request for field engineers to verify and perform the repair
- If the KPI is related to the control system of the machine, the action is typically to verify the status of the control system and re-tune it
- If the KPI is related to the process performance of the machine, then the action is in the hands of the process engineers and operators, who will decide the best way to ensure the optimal performance of the process surrounding the machine

Data-analytics platforms must automatically identify, categorize and prioritize KPIs so that the most important issues by severity and criticality are addressed first

Establishing a predictive maintenance program for rotating machines requires a systematic and methodical approach that takes into account maintenance strategies that include remote monitoring, robust data analytics and, most importantly, qualified personnel who can turn information into actionable insights that lead to lower costs, improved productivity and higher overall plant performance. ■

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Part 2

Guidelines for Designing a Compressed Air System

With the proper knowledge, engineers can work alongside compressor manufacturers to ensure that an optimal air compression system is installed

Deepak Vetal
Atlas Copco Compressors

IN BRIEF

AMBIENT CONDITIONS
CENTRALIZED VERSUS DECENTRALIZED
SIZING AND SELECTION
COMPRESSION PRINCIPLES
FLOW AND PRESSURE UNITS
RECEIVER TANK
AIR DRYER AND FILTRATION
COMPRESSOR ROOM VENTILATION
COOLING WATER
COMPRESSED AIR PIPING NETWORK
MONITORING AND CONTROL

There are various factors to consider when designing a compressed air system that help to improve the reliability and efficiency of compressors and ancillary equipment, reduce leakage and pressure drops, and minimize the compressor system's lifecycle cost (Figure 1). This article provides guidance on several considerations that impact a compressed air system.

FIGURE 1. A typical compressed air system comprises many ancillary equipment elements, and careful consideration should be taken to ensure that the system's design promotes efficiency and reliability

Ambient conditions

Compressor performance can vary based on ambient conditions. It is important to know the site elevation, ambient temperatures, relative humidity (RH) and airborne dust load prior to choosing a compressor system. Ambient air can also contain aggressive gases, such as hydrocarbons, hydrogen sulfide (H_2S) or ammonia (NH_3), which require a suitable filtration system to protect compressed air equipment. Having this information on hand can help compressed air experts make a more informed decision when it comes to designing the best solution for a plant's needs.

Centralized versus decentralized

Centralized and decentralized compressor systems each have their own advantages. A decentralized system is installed when compressed air is needed for applications where the compressor system must be located near the application, such as air blast for high-voltage electric breakers, pneumatic conveying of materials, pneumatic operation of forging tools and other applications that demand the air compressor be in close proximity.

In most other cases, a centralized system is preferred due to its added energy efficiency and decreased maintenance costs. A centralized system uses larger, but fewer, compressor units, as its air-intake filtration, ventilation requirements, cooling-water treatment, air cooling and drying are all located in the same area. Users can save time on labor and routine maintenance since centralized systems are well-suited for remote master control, load sharing and sequencing operations.

Sizing and selection

Selecting a correctly sized compressor requires a robust analysis of the following parameters:

- Flow demand
- The equipment manufacturers' flow and pressure requirements
- Air consumption rates
- Utilization factor — the ratio of time that the equipment is in operation to the total working time
- Load factor — the ratio of actual flow to the full load flow during operation time

FIGURE 2. Screw compressors provide positive displacement compression, and are well-suited for variable loads

FIGURE 3. In dynamic compressors, an impeller rotates rapidly to accelerate air to a high velocity

It is also necessary to check equipment specifications and evaluate whether or not the compressor has taken extra flow margins for leaks and pressure drops. In many cases, an additional margin on flow leads to various issues in the compressor's operation and can reduce efficiency.

Compression principles

There are two basic principles of compression for air and other gases — positive displacement and dynamic compression.

In positive displacement compression, the air is drawn into one or more of the compression chambers, which are then closed from the inlet. Gradually, the volume of each chamber decreases and the air is compressed internally. When the pressure reaches the designed build in pressure ratio, a port or valve is opened and the air is discharged into the outlet system due to the continued reduction of the compression chamber's volume. Positive displacement compressor types include piston, vane, scroll, liquid ring, rotary screw, tooth and blower. A typical compressor screw element is shown in Figure 2.

In dynamic compressors, such as radial and axial types, air is drawn between the blades on a rapidly rotating compression impeller that accelerates to a high velocity (Figure 3). The gas is then discharged through a diffuser, and the kinetic energy is transformed into static pressure. Most dynamic compressors are turbo compressors with an axial or radial flow pattern designed for larger-volume flowrates.

Selecting either of these technologies depends on the application. For instance, turbo technology is best suited for base load requirements, whereas positive displacement compressors are better for variable loads. For larger flow and variable demands, applications with

TABLE 1. TYPICAL REFERENCE CONDITIONS

Unit of measurement	Fixed reference/ standard conditions
SCFM	14.7 psia 60°F 0% relative humidity (RH) OR 14.7 psia 68°F 0% RH OR 14.7 psia 68°F 36% RH
Nm^3/h	1.01325 bara 0°C 0% RH OR 1.01325 bara 15°C 0% RH OR 1.01325 bara 20°C 0% RH

FIGURE 4. Filtration units are important components of compressed air systems, and many configurations are available, depending on the quality of air required for an application

a combination of both technologies work better for optimal utilization of compressed air and decreased energy consumption.

Flow and pressure units

An critically important first step is to decide which unit of measure will be used to indicate flowrate, based on the requirements of the specific process. There are several ways to measure the capacity of an air compressor, as follows:

- Inlet cubic feet per minute (ICFM), which is the inlet volume flowrate or intake volume as measured at the intake. For most processes, inlet flow is not usable flow; therefore, using the ICFM flow unit is not advised
- Cubic feet per minute (CFM), which describes the free air delivery as measured at the delivery point, downstream of the aftercooler
- Standard cubic feet per minute (SCFM) or normal cubic meter per hour (Nm^3/h), which represent the standard or normal flow as measured at the delivery point and established by standard temperature and pressure (STP) or normal temperature and pressure (NTP) conditions. The reference condition will have a large impact on flow, which is why it is good practice to specify the reference condition you want to use when consulting with a compressor manufacturer. Typical reference conditions are given in Table 1

Required pressure can also be specified in psig, barg or kg/cm^2g.

Receiver tank

The primary function of an air receiver tank is to store compressed air, but it also serves as an additional condensate separator. Furthermore, the air receiver ensures a steady airflow and equalizes momentary pressure variations in the air piping network, which could cause frequent loading and unloading of the compressor. Normally, the air receiver comes with a safety valve, pressure gage, connection to fit the test-pressure gage, inspection cover and drain valve.

Air dryer and filtration selection

Atmospheric air contains water vapor that must be removed to a certain degree. Water concentration increases at higher temperatures and decreases at lower temperatures. Therefore, when the air is compressed, the water concentration increases.

There are different types of dryers available on the market, with the two main types being refrigerated dryers and desiccant dryers. Refrigerated dryers can reach a 37°F pressure dewpoint, whereas desiccant dryers are capable of handling negative dewpoints. Depending on what quality of air is needed for the application, either of these dryer types can be chosen.

When sizing your dryer, avoid selecting one straight from a manufacturer's brochure. Inlet conditions can have a major impact on the dryer's performance, so it is recommended to calculate sizing based on dryer inlet conditions.

With the heatless type of desiccant

dryers, the dryers experience purge loss, which requires that designers oversize the compressors to meet that extra flow, resulting in higher energy consumption. There are also heat of compression dryers available with a zero-purge option to save on energy, as opposed to heatless dryers, since these dryers do not produce any air loss. Depending upon the application and level of energy efficiency, there are different options available to find the best solution possible.

For application or process filtration, the required filtration level and type of filters can be installed in the system piping (Figure 4). There are oil removal filters, dust filters and carbon filters available for use, depending on the quality of air required.

Compressor room ventilation

The total quantity of energy delivered to the compressor in the form of electricity is completely transformed into heat during compression. The majority of this heat is removed by a cooling medium — air or water. The remaining heat is not removed, and is referred to as the residual heat in compressed air.

In the case of water cooling, the heat is removed to outside the compressor room to the sump of the cooling tower. Conversely, with air-cooled compressors, all of the heat is dissipated into the compressor room if no dedicated ducting is provided.

Prior to deciding which type of compressor to install, make sure to procure installation proposals for both air-cooled and water-cooled options from the compressor manufacturer so that experts can help to properly size the required compressor room ventilation.

Cooling water

The cooling water quality must meet certain requirements as specified by the compressor manufacturer. It is recommended to have a water sample analyzed by a laboratory that can also advise on a suitable treatment solution if needed. The cooling water flow for compressors can be designed so that the total energy dissipated in the compressor can be evacuated with a reasonable amount of increase in water temperature.

Compressed air piping network

Compressors should be placed in a central location in close proximity to all relevant applications and processes in order to minimize the length of piping between compressors and points of use. The location must also take into consideration the quality of intake air, which should be cool, clean and dry. The compressor installation should be kept clear of steam, chemical vapors, engine exhaust and dust.

To reduce pressure drop, minimize the number of valves, bends, fittings and flow obstructions. Adequate space must be provided around the compressor for proper ventilation and for regular inspection and maintenance.

Compressed air pipes should be installed in such a way that they can be reached from all directions. Avoid pipe installations in subfloor trenches since they are difficult to maintain and repair. Also, these conditions make it difficult for adequate condensate drainage and air leak detection.

Horizontally installed pipes should slope 1 to 2% toward the air consumption point so the condensate is carried to predetermined locations where drains permit the condensate to be removed. While some may argue that properly installed and correctly sized dryers make sloping of compressed air pipes superfluous, the cost is minimal and sloping provides additional protection in the event that the dryer is out of service.

Pipe-to-tube bends should have generous radii to minimize turbulence. Bends are preferred to elbow couplings because they reduce turbulence and create less pressure drop.

To prevent condensate from entering the branch pipe, the latter should be branched on top of the subheader and condensate drain points should be provided at the lowest point of the ring network.

It is recommended to provide flanges so that sections of the air

piping network can be isolated by inserting blind flanges. Maintenance work can then be carried out without completely halting production.

Adequate brackets, clamps or other supports will keep lines straight without sagging and prevent machinery vibrations that can lead to loosened pipe couplings.

Expansion joints should be used between the compressor and air network piping with proper support after the expansion joints, which ensure that the air net load is not transferred to the equipment.

Monitoring and control

Central controllers are an effective solution for improving the efficiency of a compressed air system, because they not only monitor the system's operations, but can reduce lifecycle costs and help compressors to meet the requirements of environmental regulations. There are several advantages to central controllers for air compression systems, as described below:

- Potential energy savings (as high as 10%) on a typical compressed-air installation with mixed sizing and compressor technology
- Regulation of system pressure within a predefined and narrow pressure band to optimize energy efficiency
- Prioritized use of the most economic machines over older or less effective versions to reduce downtime
- Continuous use of variable speed drive (VSD) machines, which are the most energy-efficient machines for variable load
- Assurance that multiple VSD and/or turbo compressors are used in their most efficient performance zones when working together
- Shutdown scheduling to avoid costs during non-working hours
- Optimized pressure stability, which helps to reduce problems with air-operated equipment
- Workload equalization to avoid overloads on individual machines
- Reduced equipment maintenance costs

Central controllers are an effective solution for improving the efficiency of a compressed air system, because they not only monitor the system's operations, but can reduce lifecycle costs and help compressors to meet the requirements of environmental regulations

Comprehensive, flexible machine-sequence control ensures that installed machines are able to work in groups. The controller guarantees that the running hours of the system are equal across all machines in the same group. A central controller can also control other ancillary equipment, such as switching dryers, control valves and cooling water pumps. Users can add extra instrumentation, such as meters to monitor flow and vibration levels in order to prevent potential equipment failure. Safety parameters, temperatures and pressures can be monitored for all compressors and dryers that are connected to the controller. Furthermore, machines require fewer service visits and experience reduced costs, since they can all be serviced at the same time.

Designing a compressed air system that is right for a facility requires an understanding your applications, their demands and the different technology options available. After reviewing the information given in this article, engineers should be empowered to work knowledgeably with compressor manufacturers to design the best compression system for their application. ■

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Pressure-Relief System Design: Developments and Deficiencies

Areas of recent activity for pressure-relief systems include new calculation methods and updates to existing codes and standards. Included here is an overview of recent developments and a look at the results from a recent study of pressure-relief system deficiencies and solutions

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IN BRIEF

NEW CALCULATION METHODS

REGULATORY CODE UPDATES

SAFETY INCIDENTS

PRESSURE-RELIEF SYSTEM STUDY

COMMON ISSUES

MITIGATION OPTIONS

PRACTICAL SOLUTIONS

ADVANCED CALCULATION METHODS

STABILITY ANALYSIS

FIELD CHANGES

IMPORTANCE OF DOCUMENTATION

The process safety field is constantly changing and evolving, so it is important to periodically assess new developments that affect each of the various types of safety equipment. Pressure relief and flare systems are examples of equipment systems that have experienced recent and ongoing changes. This article focuses primarily on three areas of activity in pressure-relief systems: new calculation methods; updates to regulatory codes and standards; and lessons learned from safety events at chemical process industries (CPI) facilities. To illustrate potential problems associated with pressure-relief systems and possible mitigation options, the article also discusses the findings from a study, conducted by the authors' employer, of pressure-relief equipment at a petrochemical facility.

FIGURE 1. Pressure relief valve (PRV) stability has been an area of recent focus for API research groups

New calculation methods

New calculation methods are constantly being developed and enhanced to address both new and existing safety topics (for information on calculations for sizing pressure-relief valves, see Part 2 of this Feature Report, pp. 52–55). A few examples of this for pressure-relief systems include the following:

Two-phase flow. The Design Institute for Emergency Relief Systems (DIERS) has made two-phase flow one of its main areas of focus. Over the past three decades, DIERS has spent several million dollars to investigate the two-phase vapor-liquid onset and disengagement dynamics, as well as the hydrodynamics of emergency relief systems. Of particular interest to DIERS was the prediction of two-phase flow venting and the applicability of various sizing methods for two-phase vapor-liquid flashing flow.

Runaway reactions. In addition to advancing two-phase flow modeling, DIERS has also continued to develop and improve modeling of runaway-reaction scenarios. Over the years, more sophisticated reaction models have been developed to allow more accurate prediction and modeling of runaway reactions.

Pressure relief valve (PRV) stability. New engineering analyses have been developed

through American Petroleum Institute (API) research groups to further study PRV stability for cases where inlet line losses exceed 3% of set pressure (Figure 1). This research has demonstrated that PRVs can function in a stable manner with irrecoverable inlet losses greater than 3% of the set pressure. The research also provides an accepted methodology to determine and demonstrate stable operation of PRVs.

Acoustic induced vibration. Acoustic induced vibration (AIV) is generally a potential problem to piping in gas service where large amounts of high-frequency acoustic energy can be generated by a pressure-reducing device, such as a PRV. The flowrate and pressure primarily govern the amplitude of this energy transmitted through the piping system. Excitation due to AIV can lead to fatigue failure of downstream connections, with failures potentially occurring at small bore branches. It is important to consider this phenomenon when designing piping for pressure-relief systems, and when selecting appropriate piping and connections to prevent AIV from occurring.

Regulatory code updates

Regulatory codes and standards are continuously being updated, resulting generally in both new and stricter requirements (Figure 2). The following describe several of the recent updates to codes and standards governing pressure relief systems:

API Standard 520 Part 1 [1]. This standard applies to the sizing and selection of pressure relief devices used in petroleum refineries, chemical manufacturing facilities and related industries for equipment that has a maximum allowable working pressure (MAWP) of 15 psig (103 kPag) or greater. The pressure-relief devices covered in this standard are intended to protect unfired pressure knock-out drums and related equipment against overpressure from operating events and fire contingencies.

Part 1 of this standard was most recently updated in 2014, and it includes basic definitions and information about the operational characteristics and applications of various pressure-relief devices. It also includes sizing procedures and methods based on steady-state flow of Newtonian fluids.

API Standard 520 Part 2 [2]. This standard was most recently updated in 2015, and was also promoted from a Recommended Practice to a Standard. It covers methods of installation for pressure-relief devices in gas, vapor, steam, two-phase, and incompressible fluid service.

API Standard 521 [3]. This standard was most recently updated in 2014. It provides guidelines for a number of tasks, including evaluating the principal causes of overpressure, determining individual relieving rates and selecting and designing disposal systems. These would include such component parts as piping, vessels, flares and vent stacks.

API Standard 2000. This standard covers the normal and emergency vapor-venting requirements for aboveground liquid petroleum or petroleum-products storage tanks and aboveground and underground refrigerated storage tanks designed for operation at pressures from full vacuum through 103.4 kPag (15 psig). It was up-

FIGURE 2. Regulatory codes and standards for pressure-relief devices have seen some recent updates

dated in 2014, and discusses the causes of overpressure and vacuum, as well as the determination of venting requirements, the means of venting, selection and installation of venting devices, and testing and marking of relief devices.

This standard applies to tanks containing petroleum and petroleum products, but it can also be applied to tanks containing other liquids. However, it is necessary to use sound engineering analysis and judgment whenever this standard is applied to other liquids. This standard does not apply to external floating-roof tanks.

National emphasis programs. The U.S. Occupational Safety and Health Administration (OSHA; Washington, D.C.; www.osha.gov) Refinery National Emphasis Program and the Process Safety Management (PSM) Covered Chemical Facilities National Emphasis Program included a focus on ensuring that pressure-relief systems design documentation is kept up-to-date and accurate.

Safety incidents

Safety incidents experienced in plant operation have led the industry to rethink certain assumptions used in process safety, such as which pressure-relief scenarios are considered credible. Some examples of these incidents include the following:

Sonat Exploration Co. On March 4, 1998, a catastrophic vessel failure and fire occurred at a facility owned by Sonat Exploration in Louisiana. Four workers who were near the vessel were killed, and the facility sustained significant damage. The vessel lacked a pressure-relief system and ruptured due to overpressurization during startup. The rupture released flammable material, which ignited.

First Chemical Corp. On October 13, 2002, a violent explosion occurred in a chemical distillation tower at First Chemical in Pascagoula, Miss., sending heavy debris over a wide area. Three workers in the control room were injured by shattered glass. One nitrotoluene storage tank was punctured by explosion debris, igniting a fire that burned for several hours. During the incident investigation conducted by the U.S. Chemical Safety Board (CSB; www.csb.gov), it was determined that the capacity of the pressure-safety valve was inadequate to prevent overpressurization and catastrophic column failure.

BP plc. A major incident occurred at the BP refinery in Texas City, Tex. in March 2005. An explosion occurred when hydrocarbon vapors overflowed from a blowdown stack and ignited. The explosion resulted in 15 fatalities and 180 injuries. One of the contributing factors in this incident was the use of an inadequately designed blowdown drum and stack as part of the pressure relief and venting system for the raffinate splitter, which had gone through several design and operational changes and was located close to uncontrolled areas.

Goodyear. On June 10, 2008, Goodyear operators closed an isolation valve between a heat exchanger shell (ammonia-cooling side) and a PRV to replace a burst rupture disk under the PRV that provided overpressure protection. Maintenance workers replaced the rupture disk on that day; however, the closed isolation valve was not reopened.

On the morning of June 11, an operator closed a block valve isolating the ammonia pressure-control valve from the heat exchanger. The operator then connected a steam line to the process line to clean the piping. The steam flowed through the heat exchanger tubes, heated the liquid ammonia in the exchanger shell, and increased the pressure in the shell. The closed isolation and block valves prevented the increasing ammonia pressure from safely venting through either the ammonia pressure-control valve or the rupture disk and PRV. The pressure in the heat exchanger shell continued climbing until it violently ruptured, killing one operator and causing extensive damage.

At the time, John Bresland, former CSB chair, was quoted as saying, "This tragic accident is but the latest example of the destruction that can result from a lack of effective pressure-relief systems and practices."

Williams Olefins. On June 13, 2013, a catastrophic equipment rupture, explosion and fire occurred at the Williams Olefins Plant in Geismar, La., where two Williams employees were killed as a result. The incident occurred during nonroutine operational activities that introduced heat to an offline reboiler, creating an overpressure event while the vessel was isolated from its pressure-relief device. The introduced heat increased the temperature of the liquid propane mixture confined within the reboiler shell, resulting in a dramatic pressure rise within the vessel due to liquid thermal expansion. The reboiler shell catastrophically ruptured, causing a boiling liquid expanding vapor explosion (BLEVE) and fire.

All incidents mentioned here were investigated by the CSB and represent a limited snapshot of events that were related to pressure-relief systems, as identified in the published CSB reports at www.csb.gov.

To improve a plant's overall safety apparatus and meet the demands of the ever-changing safety world, it is necessary to address two general questions: What is the quality of the plant's current safety systems?; and How effective are the mitigation options that are available to solve problems created by inadequate design?

Pressure-relief system study

It is an unfortunate reality that process safety can often be a victim of plant economics — sufficient time and financial resources are not always available to instantly and simultaneously address every safety

issue. Because of this, it is necessary to prioritize. Formalized studies of a particular set of safety systems can offer insight about prioritization of potential safety improvements.

Presented here are the findings from a sample study of pressure relief systems that is similar to a safety audit (Figure 3). Such studies can be utilized to create a picture of where the plant stands on the whole, and enable the prioritization of pressure-relief systems that pose the greatest risks to the facility.

To help illustrate the conduct of a safety study in the context of pressure-relief systems, we describe a recent detailed analysis, carried out recently by the authors' employer, of a process unit within a petrochemical production facility. The study analyzed all pressure-relief systems throughout the process unit and judged them to be either adequate or inadequate, according to the following typical criteria:

- Pressure-relief requirement compared to relief capacity
- Irreversible inlet-line loss (3%)
- Backpressure (10% for conventional devices, manufacturer-specific for other types, such as balanced bellows)
- Installation and code-violation issues
- Temperature concerns

Common issues

The results of the analysis of pressure-relief systems revealed a number of issues, which are discussed here, along with possible mitigation options. Of the systems and calculations analyzed, a significant number were found to be inadequate for the following reasons:

- Relief capacity: 41%
- Irreversible inlet line loss: 32%
- Backpressure: 22%

The most common factors contributing to overpressure scenarios for which the existing pressure-relief systems were inadequately sized included the following:

- ***Blocked outlet***. This scenario was mainly due to the pressure-relief consequences not being considered during operational changes, such as increased plant throughput and increased operating temperatures
- ***Abnormal flow.*** This scenario was due to the original design missing a significant amount of manual valve operation situations, such as inadvertent opening of a control valve bypass valve
- ***Thermal expansion.*** This situation was due to failures of the original design to consider thermal expansion to be credible, even for heat exchangers with high heat duties
- ***Tube rupture.*** This was due to the original design being inconsistent regarding consideration of tube rupture as a credible source of overpressure. The original design did not consider mixing effects, such as flow of a volatile mixture to the hot side of the heat exchanger

FIGURE 3. A recent detailed analysis of pressure-relief devices at a petrochemical facility can inform prioritization of safety projects

External fires and control valve failures were found to result in very few inadequately sized pressure-relief systems, even though these two overpressure scenarios were commonly analyzed in the sample pressure-relief systems.

In the study, several factors were identified that contributed to the number of problematic pressure-relief calculations. The factors include:

- Original design work failed to consider specific pressure-relief scenarios
- Missing or conflicting sources of data
- Changes in plant throughput and operating conditions
- Changes regarding compliance and company guidelines

Approximately 70% of the pressure-relief systems analyzed were found to have an issue of some sort. Most of these issues involved interconnecting valves between equipment not being locked, or "car-sealed" open. These issues were easily resolved, but some other installation issues were not as easily mitigated. For example:

- PRVs set above MAWP
- Low points in the PRV outlet line, allowing pocketing of liquids

"Unprotected equipment" was evaluated to determine if there was an applicable overpressure scenario in the revalidation study. An equipment item could be considered to be unprotected if it does not have a free path to a pressure relief device, as defined by both API and ASME requirements. Several systemic deficiencies were identified:

- Some PRVs were set above the MAWP of the equipment they were protecting
- Pressure-relief devices on a common inlet manifold were not considered for hydraulic calculations
- Thermal-relief valves were often assumed to be adequate without proper evaluation of the applicable overpressure scenarios
- Some overpressure scenarios were not considered
- Manual/bypass valve opening was not considered

It is also worth noting that none of the existing documentation for the pressure relief devices evaluated met the current documentation guidance in API Standard 521, Section 4.7. For example, the existing documentation did not provide rationale regarding the credibility of all typical overpressure scenarios. This is a common issue in many facilities.

Mitigation options

When an existing pressure-relief system is found to have issues, there are many well-known and accepted "typical fixes." Included here are some of the potenial issues of pressure-relief systems, along with possible mitigation strategies:

To address inadequate capacity in the pressure-relief system, possible mitigation strategies could include:

- Installation of larger PRV
- Installation of additional PRV

- Mitigation of controlling scenario (for example, fireproof insulation for an external fire scenario)

For excessive inlet pressure losses, mitigation could involve:

- Reduce the number of fittings, elbows and so on
- Use larger inlet piping
- Increase PRV blowdown
- Install a pilot relief valve

For excessive outlet pressure losses, the following actions are possible fixes:

- Reduce the number of fittings, elbows and so on
- Use larger outlet piping
- Install a bellows-relief valve

When temperatures are above the maximum allowable working temperature, plants can use fireproof insulation or water sprays for external fire scenarios. If temperatures are below the minimum design metal temperature, plants should look to select an alternate material of construction.

It should be noted that any of these "typical" fixes do not take into account cost — and indeed may be cost-prohibitive, especially for existing facilities. Therefore, prior to making any physical modification in the facility, it is worth ensuring that every design option has been considered thoroughly. Engineering design options will tend to be a fraction of the cost of any physical modification in the plant.

Practical solutions

Several mitigation options exist to address the inadequate pressure-relief system calculations, including:

Administrative changes (for example, locking a bypass valve closed). The opening of normally closed manual bypass valves around control valves contributed significantly to inadequate relief systems; particularly control valve bypass valves and steam out valves.

Locking these valves closed affects more than just the pressure-relief area sizing — with the scenario eliminated, there is no longer a need for any inlet and outlet pressure-loss calculations for that scenario.

API Standard 521 (6th edition) currently allows the use of administrative controls to mitigate or eliminate overpressure scenarios, particularly if the accumulated pressure does not exceed the corrected hydrotest. Specific guidance is given in API Standard 521 for the following scenarios:

- Closed outlets on vessels
- Inadvertent valve opening
- Check-valve leakage or failure
- Heat transfer equipment failure (tube rupture)

Locating missing data or documentation. Missing data can be a significant factor affecting pressure-relief design calculations. Conflicting data can result in inadequate pressure-relief system design as conservative assumptions are often used in cases where discrepancies exist.

The amount of information needed to meet the OSHA PSM Standard Process Safety Information (PSI) element can be considerable, and requires revalidation every five years. There is no requirement that all PSI be compiled in a single document, or that it be located in a single file. Where it is contained in various documents or locations, good practice is to compile an index of the PSI or locations, or both.

During the National Emphasis Program audits conducted by OSHA, inadequate or outdated PSI was commonly one of the most frequently cited elements. In the case of pressure-relief systems, data discrepancies can cause inefficiencies, additional costs, and most importantly, the potential for improper relief system design.

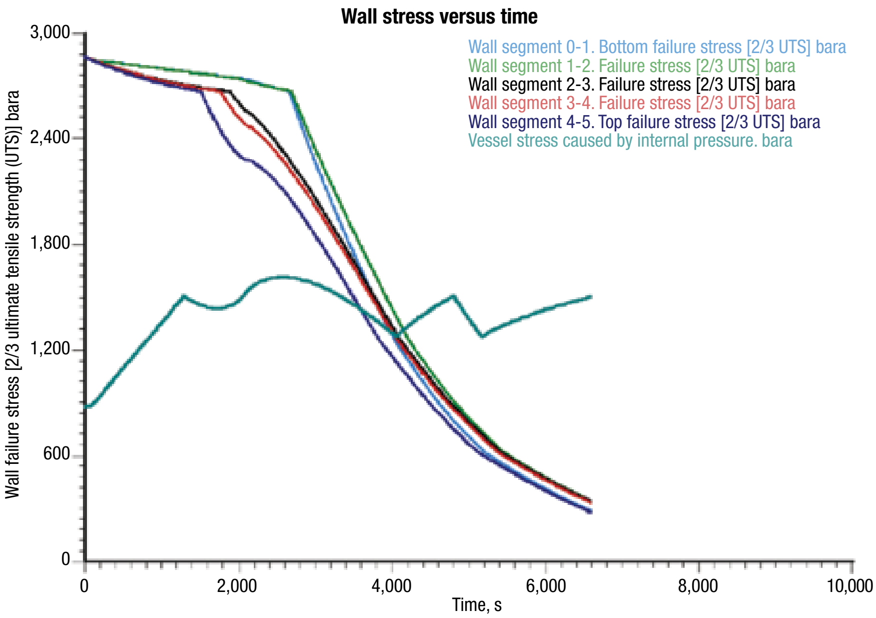

FIGURE 4. This graph shows an example of dynamic simulation to predict vessel-wall failure due to fire exposure

Advanced calculation methods

Improvements in computational power and software have led to increased availability of dynamic-relief sizing calculations.

Various relief scenarios can be modelled dynamically, such as the following: external fire; loss of cooling; tube rupture; and vapor breakthrough and liquid displacement

The benefits of a dynamic pressure-relief system simulation include a more accurate representation of the system at relief conditions, typically resulting in decreased pressure-relief flowrate requirements and required relief areas; and hence potentially smaller PRVs.

Additionally, dynamic simulations enable the user to model the effects of relief on upstream and downstream systems, such as the ability to compute changes in flow in and out of the system due to changes in pressure and temperature over time. Dynamic simulation can also be used to predict vessel wall failure due to fire exposure, as shown in Figure 4.

Stability analysis

PRV stability and the "3% rule" has been under scrutiny over the past several years as the subject of litigation, research and modeling. PRV instability can lead to chatter, which

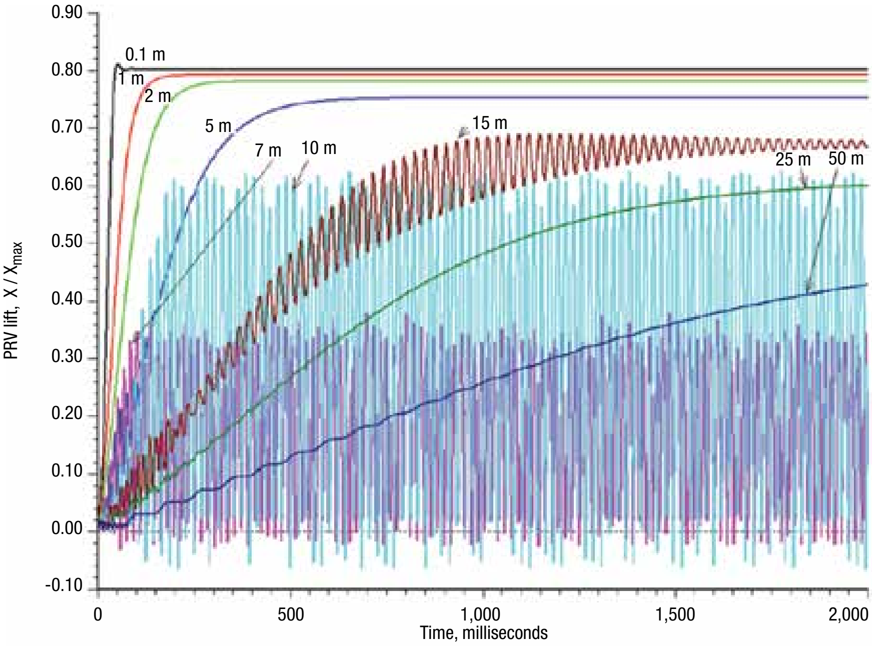

FIGURE 5. This graph shows an example of dynamic PRV stability calculations, with results from different lengths of inlet piping

in turn can result in catastrophic failure of the system. It is therefore important to ensure that when the last line of defense is asked to perform, any pressure relief devices operate in a safe and stable manner. The "3% rule" remains a recommendation and not a requirement in RAGAGEP (recognized and generally accepted good engineering practice). The "rule" appears in both ASME Boiler and Pressure Vessel Code Section VIII Division I (BPVC-VIII-I) Non-Mandatory Appendix M and as a "should" in API STD 520 Part II.

API practice formed the foundation of the ASME guidance. In the past, API RP 520 Part II has allowed an "engineering analysis" to demonstrate that non-recoverable inlet pressure drop greater than 3% of the set pressure is safe, but has offered little guidance on a method.

Based on significant research and experience, the sixth edition of API 520, now a standard, includes an engineering analysis (§7.3.6) and provides valuable guidance to the user.

While the mitigation options mentioned previously may have primarily addressed pressure-relief-system capacity inadequacies, the irreversible inlet-loss inadequacies can remain a concern. The force balance method can be used to determine if the installation of a pressure-relief device will result in stable behavior, even when inlet pressure losses exceed 3%. Figure 5 provides an example of dynamic PRV stability calculations.

Additionally, the following conclusions can be drawn, based on PRV stability research: inlet and outlet piping configuration highly impacts stability; an irrecoverable inlet loss from friction has little impact.

Field changes

Despite the previous mitigation options, some inadequate relief systems may still require actual field changes. Field changes can range from relatively easy and inexpensive jobs to troublesome and exceedingly expensive jobs. Some field changes are: installation of a bellows conversion kit; installation of a larger flow area; installation of fireproof insulation or water spray; and modification of relief-valve inlet and outlet piping

Importance of documentation

Based on the authors' experience with many pressure-relief system revalidation projects, maintaining reliable, accurate, available and maintainable pressure-relief system design documentation is an ongoing challenge for many companies. As mentioned earlier, the batch of pressure relief devices evaluated in the sample study were all lacking adequate documentation as specified in API Standard 521 (Section 4.7). It is important that updated documentation be fully compliant with these documentation requirements. When deficiencies are identified, there may not always be a simple solution to all of the safety issues. Hence, the experience and expertise of qualified safety professionals is key to identifying faults and shortcomings. ■

Edited by Scott Jenkins

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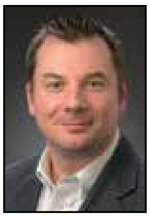

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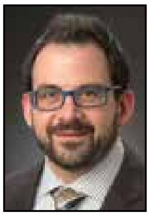

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Sizing Pressure-Relief Valves for Two-Phases

Several methods are available for sizing two-phase pressure-relief valves (PRVs). Here, the API 520 homogeneous direct integration method is compared to a potentially simpler alternative that does not require integration

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IN BRIEF

HDI VERSUS HD: AN OVERVIEW

THEORY BEHIND THE HD METHOD

SAMPLE CALCULATION

COMPARING HD AND HDI METHODS

Two-phase pressure-relief valves (PRVs) have been studied by many researchers. Among the many published works on this subject is the American Petroleum Institute (API) Standard 520 on the Sizing, Selection and Installation of Pressure-Relieving Devices. Part 1 of the API 520 standard (9th edition) describes three methods to size two-phase PRVs, which are described in detail in Annex C. The first method is the HDI (homogeneous direct integration) method (section C.2.1), which has wide applicability. The second method is known as the Omega method for two-phase flashing or non-flashing flow (described in section C.2.2). The third is the Omega method for sub-cooled liquid (described in section C.2.3).

This article examines the HDI method and compares it to an easier alternative method, known as HD (homogeneous direct without integration), which is proposed here. The HD method requires less modeling effort than the HDI method and eliminates the need for integration, but the two methods arrive at the same results, as shown in an example calculation included in this article.

HDI versus HD: An overview

The HDI method involves generating multiple data points over an isentropic range of pressures from the inlet to the discharge of the valve, using a thermodynamic property database. These data are used to evaluate the mass flux integral by direct numerical integration. When this method is put into practice, engineers generally model each isentropic integral through an expander (isentropic flash block) with 100% isentropic efficiency. Depending on the accuracy desired, this may translate into modeling ten or more isentropic flash blocks. Physical properties like pressure and mass density are extracted into a spreadsheet and mass flux is calcu-

NOMENCLATURE

c	Velocity of sound, m/s or ft/s
c_1	Velocity of sound at pressure-relief valve (PRV) discharge, m/s or ft/s
c_b	Velocity of sound corresponding to PRV backpressure, m/s or ft/s
G	Theoretical mass flux through an isentropic nozzle, kg/s-m^2 or lb/s-ft^2
h	Mass enthalpy, J/kg or Btu/lb
h_0	Mass enthalpy at stagnation state or PRV inlet or reliving condition, J/kg or Btu/lb
P	Pressure, Pa absolute (SI units) or psia (U.S. customary units)
P_0	Pressure at PRV inlet or reliving condition, Pa absolute or psia
P_1	Pressure at PRV discharge, Pa absolute or psia
P_{1a}	A pressure value imagined to calculate velocity of sound. It is equal 99% of P_1, Pa absolute or psia
ΔP	Differential pressure between P_1 and P_{1a}, Pa or psi
P_b	PRV backpressure, Pa absolute or psia
P_t	Choke pressure, or critical pressure, at the PRV throat, Pa absolute or psia
ρ_1	Mass density at the PRV discharge, kg/m^3 (SI units) or lb/ft^3 (U.S. customary units)
ρ_{1a}	Mass density corresponding to P_{1a}, kg/m^3 or lb/ft^3
$\Delta\rho$	Differential density between ρ_1 and ρ_{1a}, kg/m^3 or lb/ft^3
ρ_b	Mass density corresponding to PRV backpressure, kg/m^3 or lb/ft^3
ρ_t	Mass density at the PRV throat, kg/m^3 or lb/ft^3
v	Velocity of fluid, m/s or ft/s
v_1	Velocity of fluid at PRV discharge, m/s or ft/s
v_b	Velocity of fluid corresponding to PRV backpressure, m/s or ft/s
v_t	Velocity of fluid at the PRV throat, m/s or ft/s

lated according to the HDI method. The choke point is determined when the mass flux reaches a maximum.

The HDI method requires intensive modeling effort, depending on how close engineers need their result to compare to the actual integration (Figure 1, top). Therefore, an easier method that produces identical mass flux results without integration, would be helpful for engineeers wishing to reduce time and effort required.

The HD method without integration proposed here requires only two isentropic flash blocks (Figure 1, bottom), instead of modeling ten or more isentropic flash blocks with the HDI method. For HD, the first isentropic flash block represents the actual PRV, and is used to calculate velocity of the fluid when expanding isentropically from the PRV inlet to the PRV discharge. The second isentropic flash block is used to calculate the velocity of sound at the PRV discharge and it is an imaginary one. If the velocity of fluid is lower than the velocity of sound, it is considered a subsonic pressure relief. The mass flux can be obtained by multiplying the mass density and the velocity of fluid at the PRV discharge condition.

On the other hand, if the velocity of the fluid is greater than the velocity of sound, it is termed a supersonic relief. It is well known that supersonic pressure-relief events cannot occur without a properly designed converging and diverging nozzle. Thus, the maximum fluid velocity in a pressure-relief valve is equal to the velocity of sound. In cases where the velocity of fluid is larger, engineers need to adjust the discharge pressure of the first isentropic flash block so that velocity of fluid equals the velocity of sound. The final adjusted PRV discharge pressure is the choke or critical pressure. The adjustment can be done manually or through a solver in simulation software such as ProMax, an adjuster in HYSYS or a controller in VMGSim. Similarly, the mass flux is calculated by multiplying the mass density and velocity of fluid at this choke (or critical) pressure condition. The required relieving area can then be calculated, using formula C.9 or C.10 in the 9th edition of API 520 Part I.

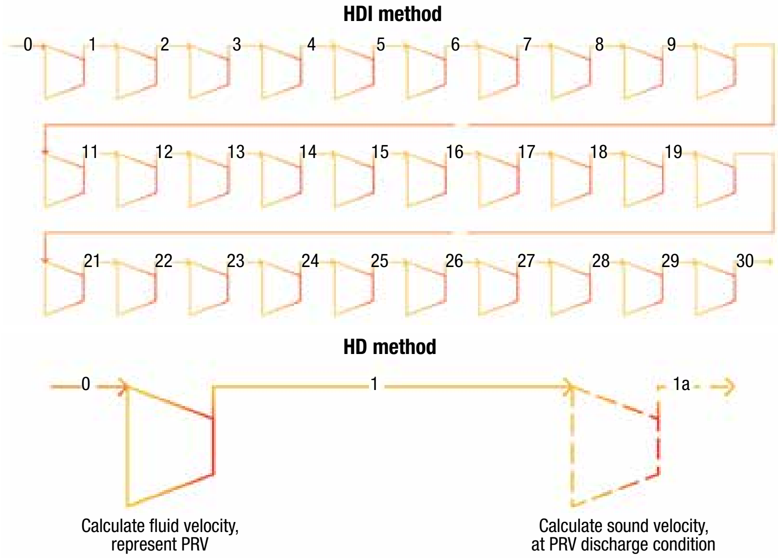

FIGURE 1. The HDI method (top) requires significant modeling effort, while the HD method without integration (bottom) reduces the modeling effort required in calculating sizes for pressure-relief valves

TABLE 1. SUBSONIC VS. SONIC RELIEF

	Subsonic Relief	Sonic relief
Criterion	$v_b < c_b$	$v_b \geq c_b$
Mass flux	$G = v_b \times \rho_b$	$G = v_t \times \rho_t$
Iterations	Once the calculation is completed, no iterations are needed	Iterations are required to find the throat pressure P_t, such that $v_t = c_t$

Theory behind the HD method

The homogeneous direct (HD) method begins with the same assumptions as those in the HDI method. The most important assumption is that the flow is well mixed — and therefore homogeneous — due to high fluid velocities and a high degree of turbulence found in typical pressure-relief flow. This means that the two-phase mixture can be represented as a "pseudo-single-phase" fluid, with properties that are a suitable average of the individual phase properties.

Fluid velocity calculation. When dealing with pressure-relief flows, it is often convenient to work with properties evaluated at a reference state known as the "stagnation state." The stagnation state is the state that a flowing fluid would attain if it were decelerated to zero velocity isentropically. Figure 2 illustrates how an actual PRV can be conceptualized into a nozzle model. Compared to the high fluid velocity at the pressure-relief valve throat, the fluid velocity at the relieving condition (PRV inlet) is negligible. Thus,

$$h_0 = h + (v^2 / 2) \quad \textbf{(1)}$$

After rearranging the formula, the fluid velocity can be calculated in SI units, as follows:

$$v = \sqrt{(2 \times (h_0 - h))} \quad \textbf{(2)}$$

Or in U.S. customary (USC) units, using the appropriate conversion factors:

$$v = \sqrt{(2 \times (h_0 - h) \times 2{,}326/0.3048^2)}$$
(3)

The variables and units for Equations (1) through (7) are described in the nomenclature box on p. 52.

Velocity of sound calculation. Velocity of sound can be calculated using the following formulas. In SI units:

$$c = \sqrt{(\Delta P/\Delta \rho)} \quad \textbf{(4)}$$

In USC units:

SAMPLE CALCULATIONS USING HD METHOD

To illustrate how to properly utilize the HD method to calculate the mass flux of a two-phase pressure relief flow, a sample problem is presented here. ProMax is used as the process simulator and ASME steam is the selected physical property package. Please refer to Figure 1 for the process flow setup. The same exercise can be done directly in an Excel spreadsheet also, if a thermodynamic engine like RefProp is installed on the computer. For this example, the following values are assigned:

Fluid: a steam and water mixture
Relieving (PRV inlet) pressure P_0: 100 psia
Relieving steam and water fraction: 50 mol.% each
Relieving flow: 100,000 lb/h
Backpressure P_b scenario 1: 80 psia (subsonic relief)
Backpressure P_b scenario 2: 14.7 psia (sonic relief)

For subsonic relief with a backpressure of 80 psia.

Step 1: Create the first isentropic flash block (expander) to calculate fluid velocity in a process simulator like ProMax. The adiabatic efficiency is 100%. The first isentropic flash block represents the PRV, which goes through an isentropic thermodynamic path. Refer to Figure 1 for additional details.
Step 2: Create the second isentropic flash block (expander) to calculate sound velocity at the PRV discharge condition. The adiabatic efficiency is also 100%. Unlike the first isentropic flash block, which represents the PRV, the second isentropic flash block is an imaginary one that does not physically exist.
Step 3: Specify the relieving conditions as the inlet conditions for the first isentropic flash block. Fluid is H_2O, P_0 = 100 psia, vapor mole fraction = 50%, mass flow = 100,000 lb/h
Step 4: Specify the discharge pressure of the second isentropic flash block. $P_{1a} = 0.99 \times P_1$ (P_1 is the first isentropic flash block discharge pressure). This can be done through the "Specifier" function in ProMax, or "Set" in HYSYS and VMGSim.
Step 5: Set the backpressure P_b as the outlet pressure of the first isentropic flash block: $P_1 = P_b = 80$ psia
Step 6: Calculate the velocity of fluid using Equation (3) and data from Table 2
$v_1 = [2 \times (-6{,}123.01 + 6{,}132.16) \times (2{,}326 / 0.3048^2)]^{0.5} = 676.6$ ft/s
Step 7: Calculate the velocity of sound using Equation (5) and data from Table 2.
$c_1 = [(80 - 79.2) / (0.3633 - 0.35984) \times 144 \times 32.174]^{0.5} = 1{,}036$ ft/s
Step 8: Compare v_1 and c_1. Since $v_1 < c_1$, this is a subsonic relief
Step 9: Calculate the mass flux using Equation (6).
$G = 676.6 \times 0.3633 = 245.8$ lb/s-ft^2

For sonic relief with a backpressure of 14.7 psia

For Steps 1–4, follow the same protocol as in the above subsonic-relief example, then proceed as follows:
Step 5: Set backpressure P_b as the outlet pressure of the first isentropic flash block ($P_1 = P_b = 14.7$ psia)
Step 6: Calculate the velocity of the fluid using Equation (3) and data from Table 3.
$v_b = [\, 2 \times (-6{,}123.01 + 6{,}197.88) \times (2{,}326 / 0.3048^2)]^{0.5} = 1{,}936.2$ ft/s
Step 7: Calculate the velocity of sound using Equation (5) and data from Table 3.
$c_b = [(14.7 - 14.553) / (0.07411 - 0.07342) \times 144 \times 32.174]^{0.5} = 993$ ft/s
Step 8: Compare v_b and c_b. Since $v_b > c_b$, this is a sonic relief, although it looks like a supersonic relief, which is impossible in a PRV pressure-relief situation.
Step 9: Increase the discharge pressure of the first isentropic flash block to P_t, then repeat Steps 6 and 7 until $v_t = c_t$. This can be done manually or through a solver in the ProMax software, an adjuster in HYSYS or a controller in VMGSim. The final adjusted pressure is the critical pressure, or choke pressure, P_t at the throat. At these choke conditions, P_t = 59.31 psia, v_t = 1,031.4 ft/s and ρ_t = 0.27362 lb/ft^3
Step 10: Calculate mass flux using Equation (7). $G = 1031.4 \times 0.27362 = 282.2$ lb/s-ft^2
Editor's note: *For more data on the sample calculations, see Tables 2 and 3 in the online version of this article at www.chemengonline.com.*

$$c = \sqrt{(\Delta P / \Delta\rho \times (144 \times 32.174))} \quad (5)$$

Mass flux calculation. Mass flux is mass flowrate per unit area. It can be calculated by multiplying mass density by velocity. For subsonic pressure relief, the equation is as follows:

$$G = v_b \times \rho_b \quad (6)$$

The equation for a sonic pressure relief is as follows:

$$G = v_t \times \rho_t \quad (7)$$

To determine whether the pressure relief is a sub-sonic or sonic relief, first use P_b as the discharge pressure of the first isentropic flash block, and then calculate the velocity of the fluid (v_b; Equation (2) or (3)) and velocity of sound (c_b; Equation (4) or (5)). If $v_b < c_b$, then it should be considered a subsonic relief. If $v_b = c_b$, then it is a sonic relief. If $v_b > c_b$, then it is a supersonic relief, which can't happen in a PRV situation. Thus, the discharge pressure needs to increase to P_t, so that $v_t = c_t$, and the mass flux should be calculated with properties at the throat condition, instead of the backpressure condition. Sample calculations using this method are shown in the box at the top of this page.

Comparing the methods

The same example problem can be also solved with HDI method. A summary table of the calculation using the HDI method can be found in the online version of this article. It can be found at www.chemengonline.com. Refer to section C.2.1 of API 520 Part I (9th ed.) for the detailed step-by-step calculation. A table summarizing the result from the two methods can be found online. At the backpressure of 80 psia (subsonic relief), both methods yield an identical mass flux of 245.8 lb/s-ft^2. Furthermore, for a sonic relief with a backpressure of 14.7 psia, both methods capture the identical throat

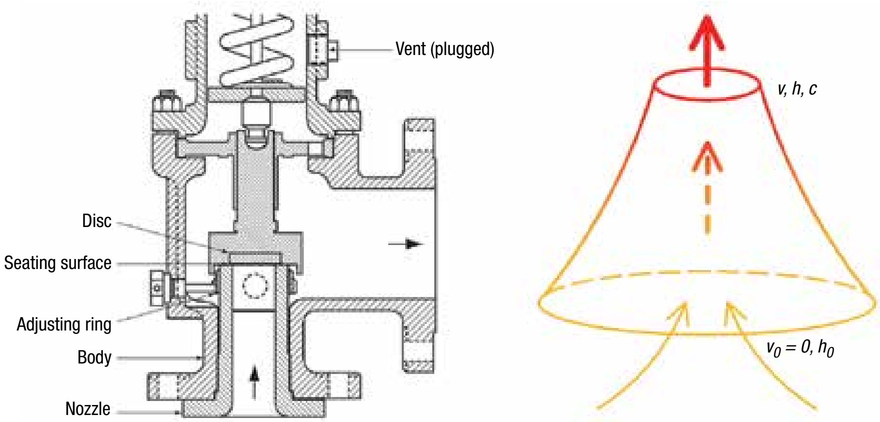

FIGURE 2. On the left, a diagram of an actual pressure-relief valve is shown, while on the right is a conceptualized nozzle model

pressure at about 60 psia and calculate an identical mass flux of 282.2 lb/s-ft^2.

The example clearly shows that the HDI and HD methods produce identical results. But the HD method is generally easier to put into practice by engineers, since it eliminates the integration and requires less modeling effort. In addition, the HD method does not involve any mathematical derivation, such as the mass flux formula in the HDI method. Overall, the HD method is easier and more straightforward for engineers to understand. ■

Edited by Scott Jenkins

Editor's note: For additional tables related to this article, see the online version at www.chemengonline.com. For more information on pressure-relief system design, see the article on pp. 44–50 of this issue.

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TABLE 2. SUB-SONIC RELIEF CALCULATION SUMMARY FOR 80 PSIA BACKPRESSURE				
		0	1*	1a
Vapor Quality	%	50.00	50.13	50.13
Pressure P	psia	100	80.00	79.20
Temperature T	F	327.9	312.1	311.4
Entropy S	Btu/lb-F	1.88	1.88	1.88
Enthalpy H	Btu/lb	-6123.01	-6132.16	-6132.56
Density ρ	lb/ft^3	0.44935	0.36330	0.35984
Fluid Velocity v	ft/s	0	676.6	
Sound Velocity c	ft/s		1036	
Status			Sub-sonic	
Mass Flux G	lb/s-ft^2		245.80	

* Pressure at point 1 equals the backpressure of 80 psia.

TABLE 3. SONIC RELIEF CALCULATION SUMMARY FOR 14.7 PSIA BACKPRESSURE						
		Initial Back Pressure Calculation			Final Result	
		0	1**	1a	Throat**	throat_a
Vapor Quality	%	50.00	50.32	50.31	50.25	50.25
Pressure *P*	psia	100	14.70	14.553	59.31	58.72
Temperature *T*	F	327.9	212.0	211.5	292.0	291.3
Entropy *S*	Btu/lb-F	1.88	1.88	1.88	1.88	1.88
Enthalpy *H*	Btu/lb	–6123.01	–6197.88	–6198.25	–6144.26	–6144.66
Density ρ	lb/ft^3	0.44935	0.07411	0.07342	0.27362	0.27103
Fluid Velocity *v*	ft/s	0	1936.2		1031.4	
Sound Velocity *c*	ft/s		993		1031.4	
Status					Sonic	
Mass Flux G	lb/s-ft^2				282.20	

** Pressure at point 1 is the initial calculation with backpressure of 14.7 psia. Pressure at point "throat" is the final choke or critical pressure

TABLE 4. HDI METHOD SUMMARY TABLE				
Pressure	**Density**	**Integrand**	**Summa-tion**	**Mass Flux**
psia	lb/ft^3	ft^2/s^2	ft^2/s^2	lb/s-ft^2
100	0.4494		0	
98	0.4408	–20820	–20820	89.9
96	0.4322	–21230	–42050	125.3
94	0.4236	–21656	–63706	151.2
92	0.4150	–22100	–85806	171.9
90	0.4064	–22563	–108368	189.2
88	0.3978	–23046	–131414	203.9
86	0.3892	–23550	–154964	216.7
84	0.3805	–24077	–179041	227.7
82	0.3719	–24629	–203669	237.4
80	0.3633	–25206	–228876	245.8
78	0.3547	–25812	–254688	253.1
76	0.3460	–26449	–281136	259.5
74	0.3374	–27118	–308254	264.9
72	0.3287	–27822	–336076	269.5
70	0.3201	–28564	–364640	273.3
68	0.3114	–29348	–393988	276.4
66	0.3027	–30177	–424166	278.8
64	0.2940	–31055	–455221	280.6
62	0.2853	–31987	–487208	281.7
60	0.2766	–32978	–520186	282.2
58	0.2679	–34033	–554219	282.1
56	0.2592	–35159	–589378	281.4
54	0.2504	–36364	–625742	280.2
52	0.2417	–37657	–663400	278.4
50	0.2329	–39048	–702447	276.1
48	0.2241	–40547	–742994	273.2
46	0.2153	–42169	–785163	269.8
44	0.2065	–43930	–829094	265.9
42	0.1977	–45849	–874942	261.5
40	0.1888	–47947	–922889	256.5

TABLE 5. MASS FLUX COMPARISON BETWEEN HDI AND HD METHOD				
			HDI Method	HD Method
Sub-sonic relief	Mass flux	lb/s-ft^2	245.8	245.8
Sonic relief	Mass flux	lb/s-ft^2	282.2	282.2
	Choke pressure	psia	60	59.31

Understanding New PPE Regulations

The new European Union Personal Protective Equipment (PPE) Regulation explained, and what it means for the chemical process industries

Bob Wells and Graham Clements
BSI

The European Commission's Personal Protective Equipment (PPE) Directive 89/686/EEC is over 20 years old and is now being superseded by the new PPE regulation (EU) 2016/425. This new regulation has been designed to reflect current technologies and processes for developing and bringing PPE to the market, as well as to enhance consumer safety and ensure fair competition between companies. The new regulation carries some important implications for the chemical process industries (CPI), which utilize a wide range of PPE to protect staff against potentially serious health and safety risks. This article outlines the new PPE regulation and describes its implications for the CPI.

PPE defined for regulations

PPE encompasses hundreds of products, including protective clothing, helmets, hearing and respiratory protection, gloves, body armor, boots and more (Figure 1). From legal and regulatory perspectives, PPE is defined more specifically as follows:

A. Equipment designed and manufactured to be worn or held by a person to protect against one or more risks to the person's health or safety

B. Interchangeable components for equipment referred to in Point A that are essential for its protective function

C. Connection systems for equipment referred to in A that are not held or worn by a person, that are designed to connect that equipment to an external device or to a reliable anchorage point, that are not designed to be permanently fixed, and that do not require fastening works before use

FIGURE 1. Personal protective equipment falls into one of three categories: simple, intermediate or complex

PPE falls into the following three categories, with Category 3 covering many serious risks of relevance to the CPI:

Category 1. This category covers "simple PPE" designed to protect users against minimal risks, including contact with hot surfaces not exceeding 50°C, contact with water or cleaning materials of weak action, and superficial mechanical injury (manufacturer's self-declaration).

Category 2. This category covers "intermediate PPE," such as safety spectacles and goggles, industrial helmets, bump caps, high-visibility clothing and other products not included in Categories 1 and 3 (EU Type Examination Certificate issued by a notified body).

Category 3. This category covers "complex PPE" to guard against risks that may cause serious consequences, such as death or irreversible damage to health (EU Type Examination Certificate issued by a notified body and ongoing assessment of factory production control). It includes risks known to arise — some of them frequently — in chemical processing facilities, such as:

- Hazardous substances / mixtures
- Harmful biological agents
- Ionizing radiation
- Oxygen-deficient atmospheres
- High-temperature environments, the effects of which are comparable to those of an air temperature of at least 100°C
- Low-temperature environments, the effects of which are comparable to those of an air temperature of –50°C or lower

The new regulation

The PPE Directive is now being superseded by the European Regulation on Personal Protective Equipment. The regulation was adopted on February 12, 2016 and published in the European Union Official Journal. It will apply to products from April 21, 2018, with a one-year transition period until April 21, 2019 for the transfer of certified products from the Directive to the new regulation.

Counterfeit, substandard and illegal PPE products do not perform as they should, and put employees' lives at risk and expose their organization to prosecution

The PPE Regulation is mandatory in every E.U. country, covering any type of product that falls within its scope. It is a legal obligation for all PPE manufactured after April 21, 2019 to comply. In addition, those involved in procuring PPE, such as health and safety professionals, facilities managers and specialist buyers, need to be aware of the changes to ensure equipment meets the requirements of the new regulation.

The main changes that the regulation brings include the following:

- Clear placement of protection from substances and mixtures hazardous to health in Category 3 (Complex PPE)
- The need for product risk assessments in the product technical file
- Enclosing a declaration of conformity with each item of PPE or at least a link to where such a document can be obtained
- Made-to-order PPE is now covered in the regulation
- The need for manufacturers to place their name and address on the product
- Responsibilities outlined for importers and distributors
- Mandatory 5-year certificate validity

PPE for hazardous substances

All PPE that claims any protection from chemical substances is included in Category 3, with the exception of water or cleaning materials of weak action. This includes toxic industrial chemicals (TIC), toxic industrial materials (TIM), and chemical warfare agents (CWA). Typical PPE for protection from these hazards includes hoods, eyewear, respiratory protection, clothing, gloves and footwear. A combination of standards and technical specifications may be required to demonstrate compliance with the essential health and safety requirements of the new regulation, and the protection may consist of combined devices or complete ensembles.

The most complex area for determining compliance is with protective clothing. Tables 1 and 2 show some of the options that are available:

New glove standards

The group of standards that apply to chemical risks for gloves has also been recently updated with changes to parts of the classification system:

- BS EN ISO 374-1:2016: Terminology and performance requirements for chemical risks
- BS EN 374-2:2014: Determination of resistance to penetration
- BS EN 374-4:2013: Determination of resistance to degradation by chemicals
- BS EN ISO 374-5:2016: Terminology and performance requirements for micro-organisms risks
- BS EN 16523-1:2015: Determination of material resistance to permeation by chemicals

Countering counterfeits

There is a good amount of effective PPE available to the CPI, but there are also numerous counterfeit and illegal products. Invariably, such fakes do not perform as they should, put employees' lives at risk and expose their organization to prosecution.

From the laboratory to the factory floor, PPE is vital to workplace wellbeing and it is imperative that it meets or exceeds health and safety standards. The new Regulation will help prevent companies from selling substandard PPE without accountability. Under the new regulation, any company importing or distributing PPE products will have to ensure it meets the regulation and keeps records.

Certification of PPE

So how can specifiers and buyers of PPE in the CPI be confident a product will do what it claims? Commercial specifiers and buyers of PPE can derive a measure of reassurance about the quality and safety of products from the presence of the "CE Mark." The presence of the CE Mark on a product means that a manufacturer claims it conforms to minimum legal requirements for the product as laid down by the E.U.

CE (conformité Européenne) Mark. For products sold within the E.U., PPE manufacturers must CE mark products following the specific requirements laid down in the regulations. The CE Mark requirements may be achieved by demonstrating that the product meets the Essential

TABLE 1. SUIT TYPES FOR PROTECTIVE CLOTHING				
"Type"	Name	Corresponding European/ISO standards	U.S. type	Definition
Type 1	Gas-tight suit	EN 943-1:2015/EN 943-2 (ET) / ISO 16602	Level A	Gas/vapor-tight suits 1a Internal SCBA, 1b External SCBA, 1c BA air line. Revised EN 943-1 awaiting harmonization
Type 2	Ventilated suit	EN 943/1:2002/ISO 16602	Level B (Approx)	Ventilated positive pressure suits with BA air line. Not included in EN 943-1:2015
Type 3	Chemical splash	EN 14605 (EN 466) / ISO 16602	Level B (SCBA) Level C (mask/ PAPR)	Suits intended to protect from strong and directional jet sprays of liquid chemical. Includes Partial body garments [PB]. Used with mask/SCBA/PAPR
Type 4	Chemical coverall	EN 14605 (EN 465) / ISO 16602	Level C	Suits intended to protect from a saturating spray of liquid chemicals. Includes Partial body garments [PB]. Used with mask/SCBA/PAPR
Type 5	Dust coverall	EN ISO 13982-1 / ISO 16602	Level D	Protection from airborne solid particulates. Used with facepiece/mask/PAPR
Type 6	Light chemical coverall	EN 13034/ISO 16602	Level D	Limited protection from light liquid chemical splashes and mist spray. Includes Partial body garments [PB]. Used with facepiece/mask/PAPR
Solid particles and Nuclear	Ventilated suit	EN 1073-1	-	Ventilated positive pressure suits for solid particles and radioactive contamination. Used with BA air line
Nuclear	Unventilated coverall	EN 1073-2	Level D	Limited protection from particulate radioactive contamination. Used with mask/ SCBA/PAPR
Airline	BA air line with hood, half suit, suit	EN 14594	-	Suitable for lower level suits when combined with type 3, 4, 5 & 6 including Partial body garments [PB]
Powered air-purifying respirator	PAPR with hood, half suit, suit	EN 12941	-	Treated as a large 'hood'. Suitable for lower level suits when combined with type 3, 4, 5 & 6 including Partial body garments [PB]

TABLE 2. PROTECTIVE CLOTHING ADD-ON REQUIREMENTS				
Additional property		Standard	Classes of protection	Definition
Chemical		EN 16523-1 or EN ISO 6529	1 to 6	Determination of material resistance to permeation by chemicals
Anti-static		EN 1149-5	Dissipative	Electrostatic properties
Infective agents		EN 14126	Class ratings for four properties	Protective clothing against infective agents
Limited flame		EN ISO 14116	Index 1/2/3	Limited flame spread
Heat and Flame		EN ISO 11612	A1/A2/B1-3/ C1-4/D1-3/ E1-3/F1-3/W	Protective clothing against heat and flame
Welding		EN ISO 11611	Class 1/2/ A1/A1+A2	Welding and allied processes
Electrical		EN 50286:2001	Class 00	Protective clothing for low-voltage installations

Health and Safety Requirements included in Annex II of the regulation. This may be through a harmonized European Standard, published in the Official Journal of the European Union (giving presumption of conformity), or through other European, national, international, publicly available standards or an appropriate technical specification.

A CE Mark placed on a product covers all the directives and regulations that apply to it, and there can be several relating to a single product, which may include the EMC Directive, Low-Voltage Directive, and Medical Devices Directive.

BSI Kitemark. BSI's status as a notified body for many European directives and regulations enables it to offer third-party testing and factory production control assessments, where products require it, and can offer support for PPE manufacturers wishing to CE Mark their products.

The BSI Kitemark is voluntary, independent, third-party certification. To achieve it, a manufacturer must have a comprehensive quality management system based on ISO 9001, or a recognized factory production control system, combined with initial product type-testing and regular ongoing audits. The certification process demonstrates the product has been manufactured under a verified quality system, and the products and processes are assessed on a continuing basis. In addition, it provides verification that the product meets the standard, as it requires regular factory visits, typically twice a year, and an ongoing product audit. Certification to, and display of, an independent BSI Kitemark provides a much stronger statement of product quality than a CE Mark, enabling customers — including those in the CPI — to differentiate between PPE and derive genuine assurance of product quality and fitness for purpose. From a buyer's perspective, it helps differentiate well-made PPE products from those of a lower standard — or indeed counterfeit goods.

BSI works both with PPE manufacturers that achieve CE marking and also with those that choose to go for BSI Kitemark certification to demonstrate product quality and generate customer trust. ■

Edited by Scott Jenkins

Authors

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Graham Clements joined BSI in 2014 as certification manager for PPE (Phone: +44 20 8996 7248; Email: product.certification@bsigroup.com. He has over 25 years' experience in PPE and assurance and has worked with industry and government bodies within the field of chemical protection. He is passionate about ensuring products have been tested to the highest level, that a product will perform as expected and protect people, property and the environment and that it will do what it is designed to do.

Economic Indicators

2015 2016 2017 2018

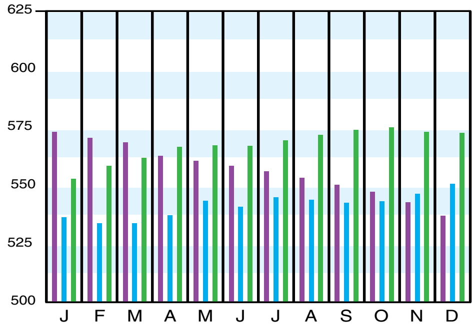
Download the CEPCI two weeks sooner at www.chemengonline.com/pci

CHEMICAL ENGINEERING PLANT COST INDEX (CEPCI)

(1957-59 = 100)	Dec. '17 Prelim.	Nov. '17 Final	Nov. '16 Final
CE Index	572.8	573.2	550.9
Equipment	691.8	692.5	661.0
Heat exchangers & tanks	604.7	604.4	573.7
Process machinery	694.7	693.2	667.9
Pipe, valves & fittings	893.5	900.1	833.9
Process instruments	410.9	411.6	396.9
Pumps & compressors	996.4	995.9	973.5
Electrical equipment	524.1	523.5	512.1
Structural supports & misc.	732.7	731.7	713.9
Construction labor	329.9	329.5	324.4
Buildings	567.2	567.5	547.0
Engineering & supervision	309.3	308.6	313.6

Starting with the April 2007 Final numbers, several of the data series for labor and compressors have been converted to accommodate series IDs that were discontinued by the U.S. Bureau of Labor Statistics

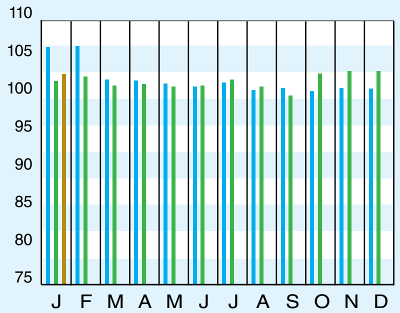
Annual Index:
2009 = 521.9
2010 = 550.8
2011 = 585.7
2012 = 584.6
2013 = 567.3
2014 = 576.1
2015 = 556.8
2016 = 541.7



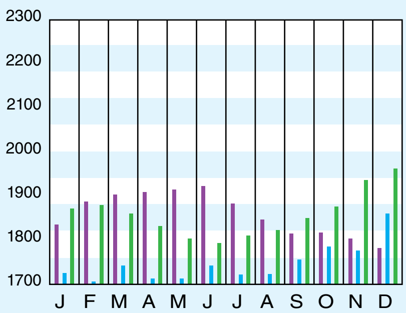
CURRENT BUSINESS INDICATORS

	LATEST	PREVIOUS		YEAR AGO
CPI output index (2012 = 100)	Jan. '18 = 102.8	Dec. '17 = 102.7	Nov. '17 = 103.0	Jan. '17 = 100.7
CPI value of output, $ billions	Dec. '17 = 1,962.9	Nov. '17 = 1,944.5	Oct. '17 = 1,889.1	Dec. '16 = 1,828.2
CPI operating rate, %	Jan. '18 = 76.7	Dec. '17 = 76.8	Nov. '17 = 77.0	Jan. '17 = 75.8
Producer prices, industrial chemicals (1982 = 100)	Jan. '18 = 267.2	Dec. '17 = 269.8	Nov. '17 = 262.2	Jan. '17 = 241.5
Industrial Production in Manufacturing (2012=100)*	Jan. '18 = 104.8	Dec. '17 = 104.7	Nov. '17 = 104.8	Jan. '17 = 103.0
Hourly earnings index, chemical & allied products (1992 = 100)	Jan. '18 = 187.2	Dec. '17 = 183.9	Nov. '17 = 182.2	Jan. '17 = 170.1
Productivity index, chemicals & allied products (1992 = 100)	Jan. '18 = 100.9	Dec. '17 = 102.5	Nov. '17 = 102.0	Jan. '17 = 103.3

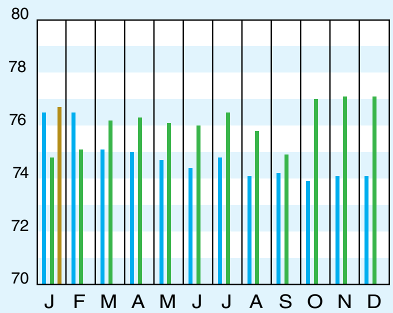
CPI OUTPUT INDEX (2000 = 100)†



CPI OUTPUT VALUE ($ BILLIONS)



CPI OPERATING RATE (%)



*Due to discontinuance, the Index of Industrial Activity has been replaced by the Industrial Production in Manufacturing index from the U.S. Federal Reserve Board.
†For the current month's CPI output index values, the base year was changed from 2000 to 2012
Current business indicators provided by Global Insight, Inc., Lexington, Mass.

CURRENT TRENDS

The preliminary value for the December *CE* Plant Cost Index (CEPCI; top; most recent available) decreased compared to the previous month's value for the second consecutive month. Decreases in the Equipment and Buildings subindices for December 2017 offset small increases in the Construction Labor and Engineering & Supervision subindices. Within the Equipment subindex, a number of equipment classes saw decreases, with the largest being in Pipes, Valves and Fittings. The overall monthly CEPCI value for December 2017 stands at 4.0% higher than the corresponding value from December 2016. Meanwhile, the latest Current Business Indicators (CBI; middle) for January 2018 showed slight gain in the CPI Output Index.